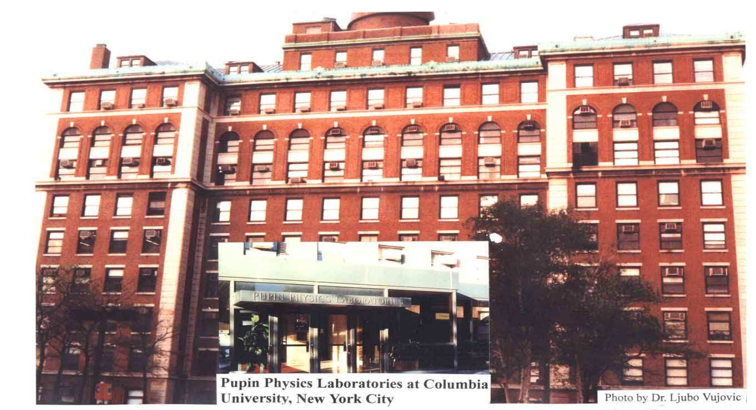
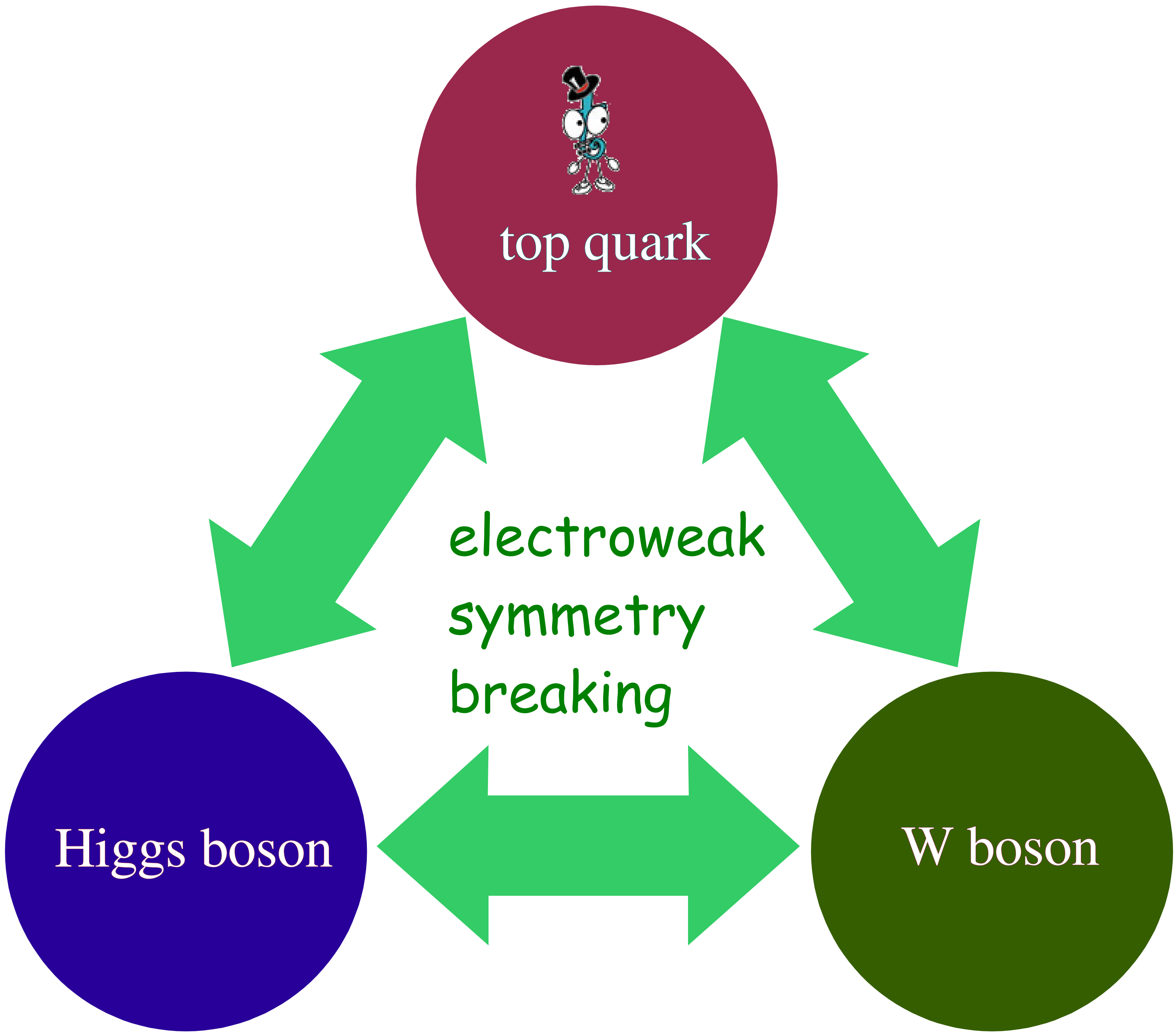
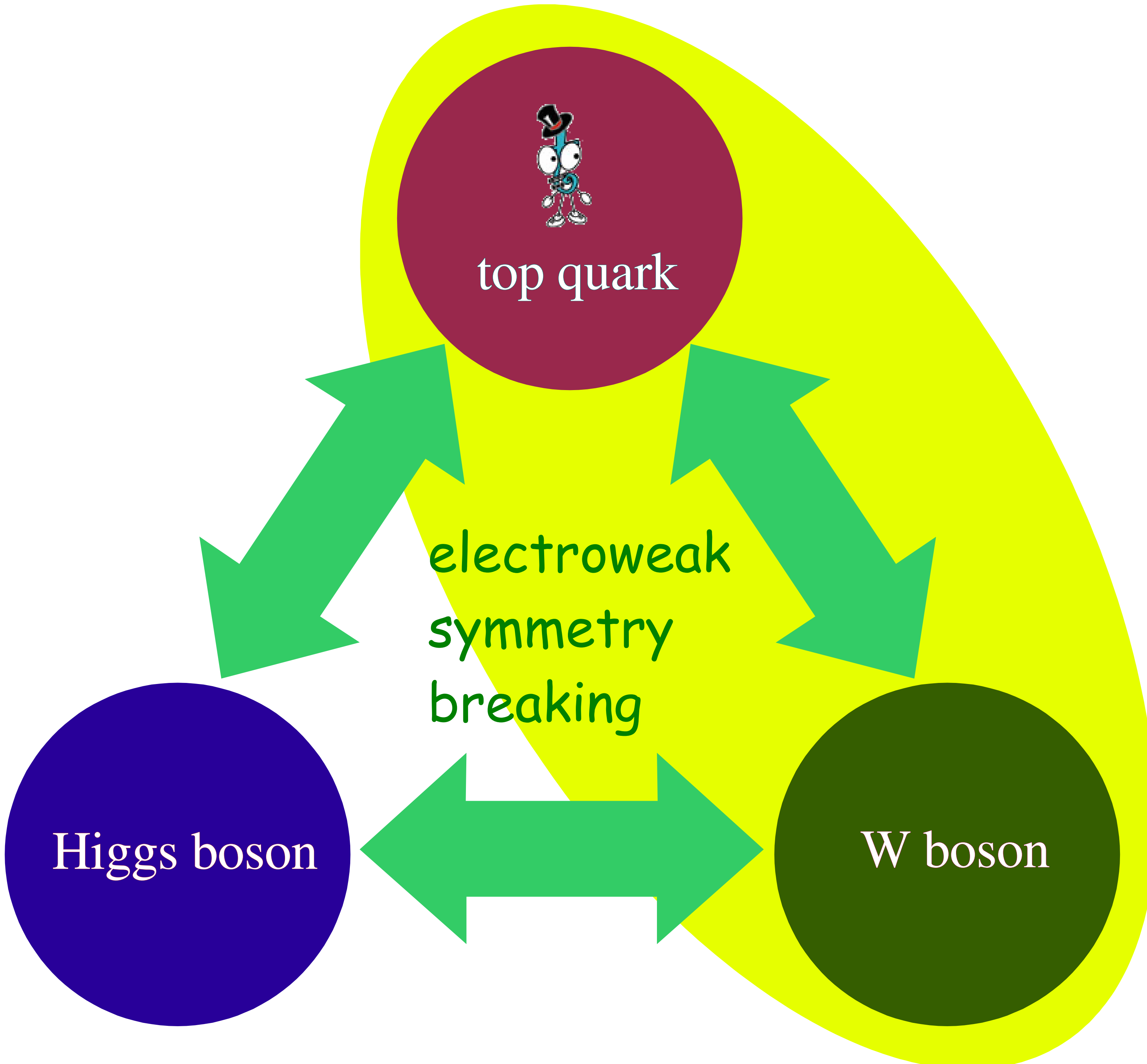
Search for Single Top Quark Production at DØ in Run II

Reinhard Schwienhorst



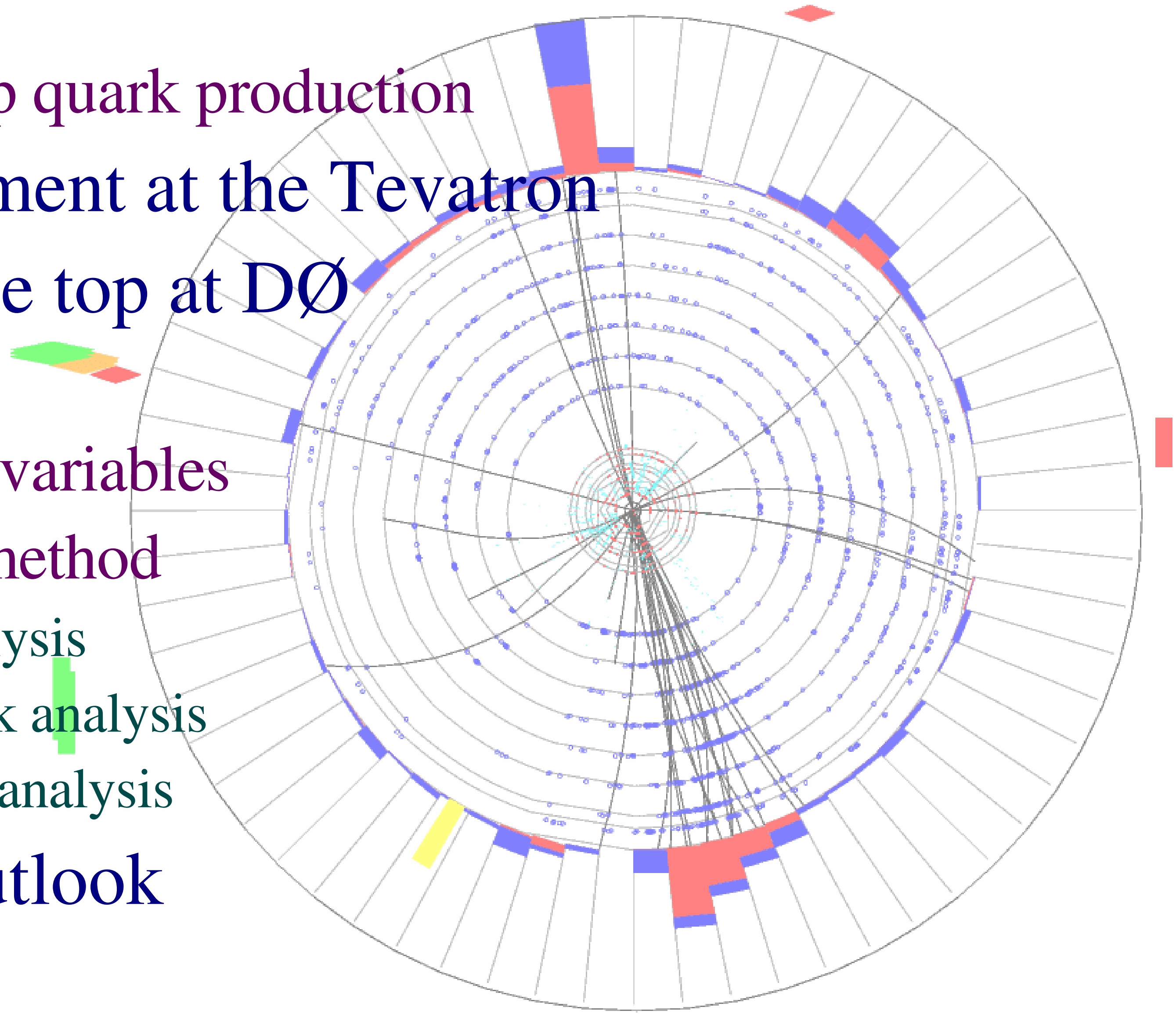
Columbia University Nuclear/Particle & Astroparticle Seminar, 4/27/2005


top quark
electroweak
symmetry
breaking
Higgs boson
W boson


top quark
electroweak
symmetry
breaking
Higgs boson
W boson

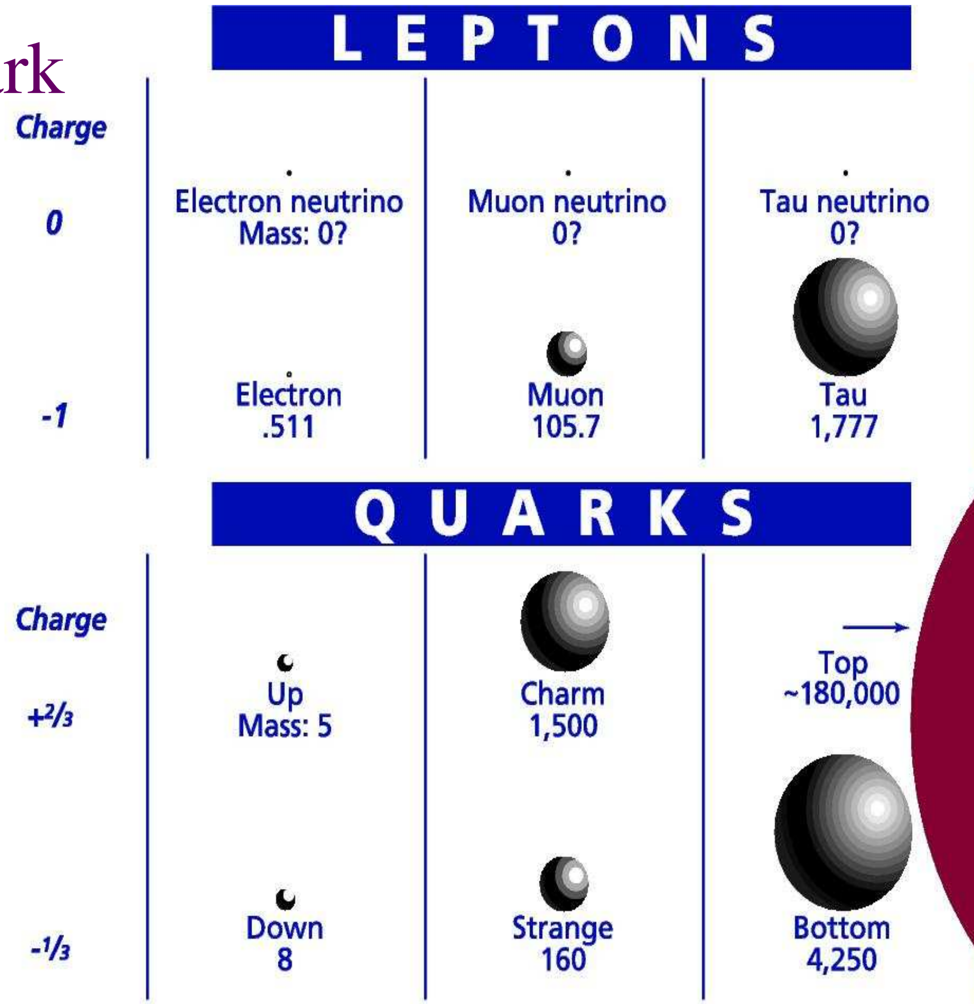
Outline

- Introduction
  - Top quark
  - Electroweak top quark production
- The DØ experiment at the Tevatron
- Search for single top at DØ
  - Event selection
  - Discriminating variables
  - Final analysis method
    - Cut-based analysis
    - Neural network analysis
    - Decision Tree analysis
- Conclusions/Outlook



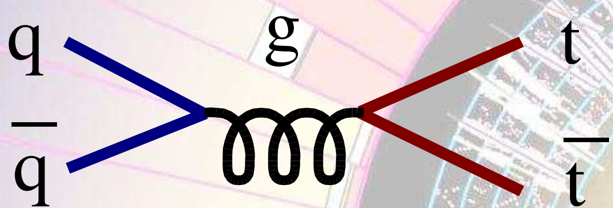
Top Quark

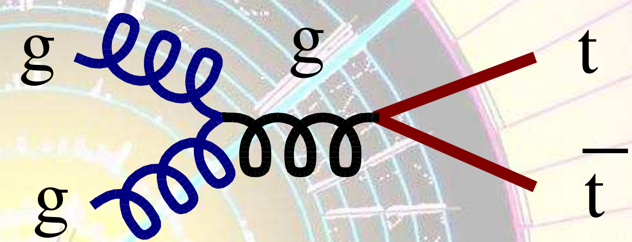
- Discovered in 1995 by CDF and DØ at the Tevatron
- Heaviest of all fermions
  - 40 times heavier than b quark
- Only quark that decays before it hadronizes
  - Clean laboratory to study quark properties
- Couples strongly to SM Higgs boson
  - Electroweak symmetry breaking



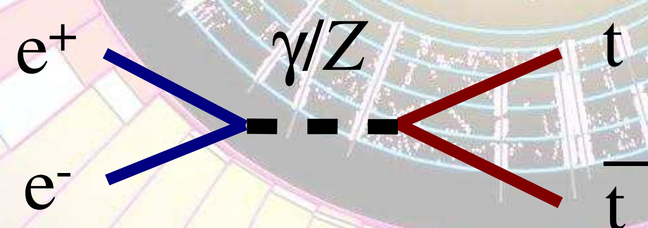
Fundamental Interactions

- Strong force
  - Top quark production in hadron colliders





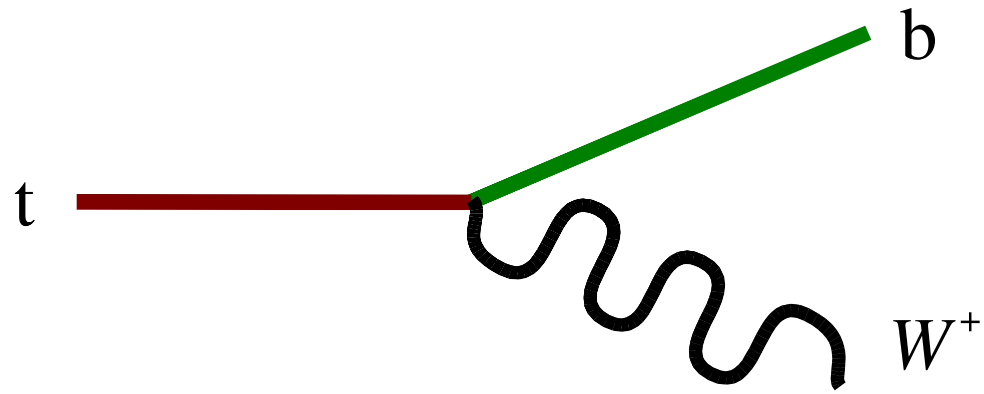
- Electroweak neutral current
  - Top quark production in lepton colliders



Top quark pair creation

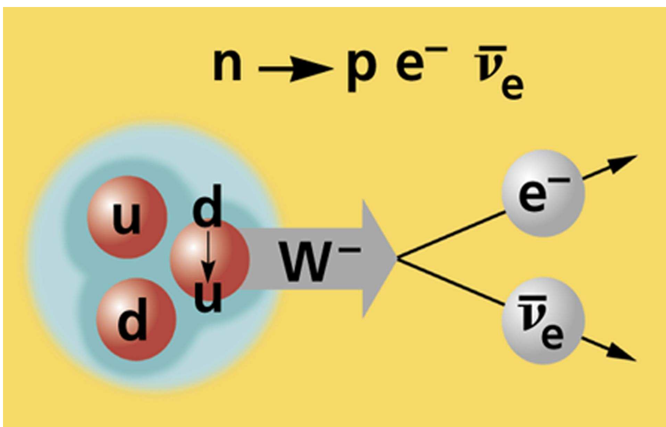
Top Quark Interactions

- Electroweak charged current
  - So far, we only really know that it does decay

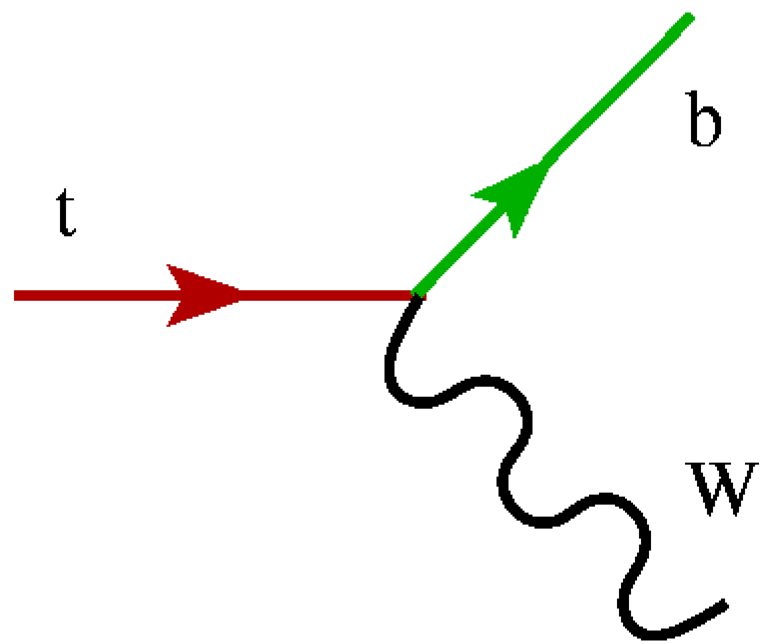


Top quark decay

– Electroweak charged current also responsible for nuclear Beta decay



Top Quark Electroweak Interaction

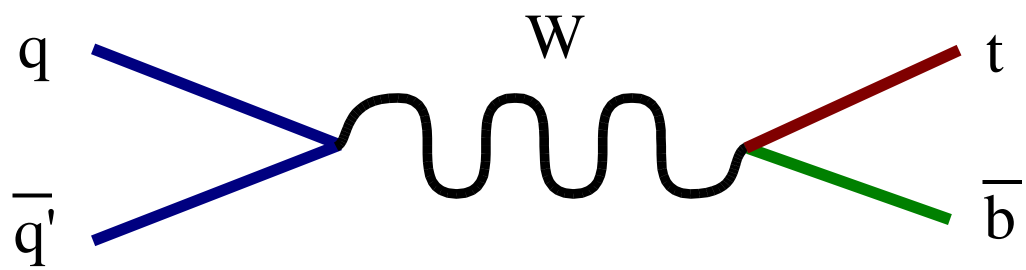


top quark decay

Wtb vertex has many angles

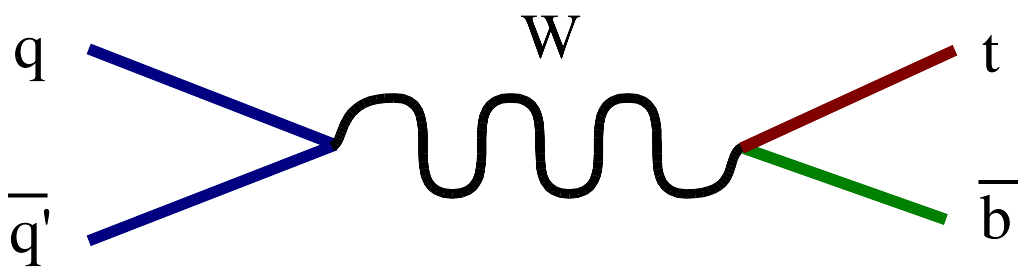
Electroweak Production of Top at the Tevatron

s-channel

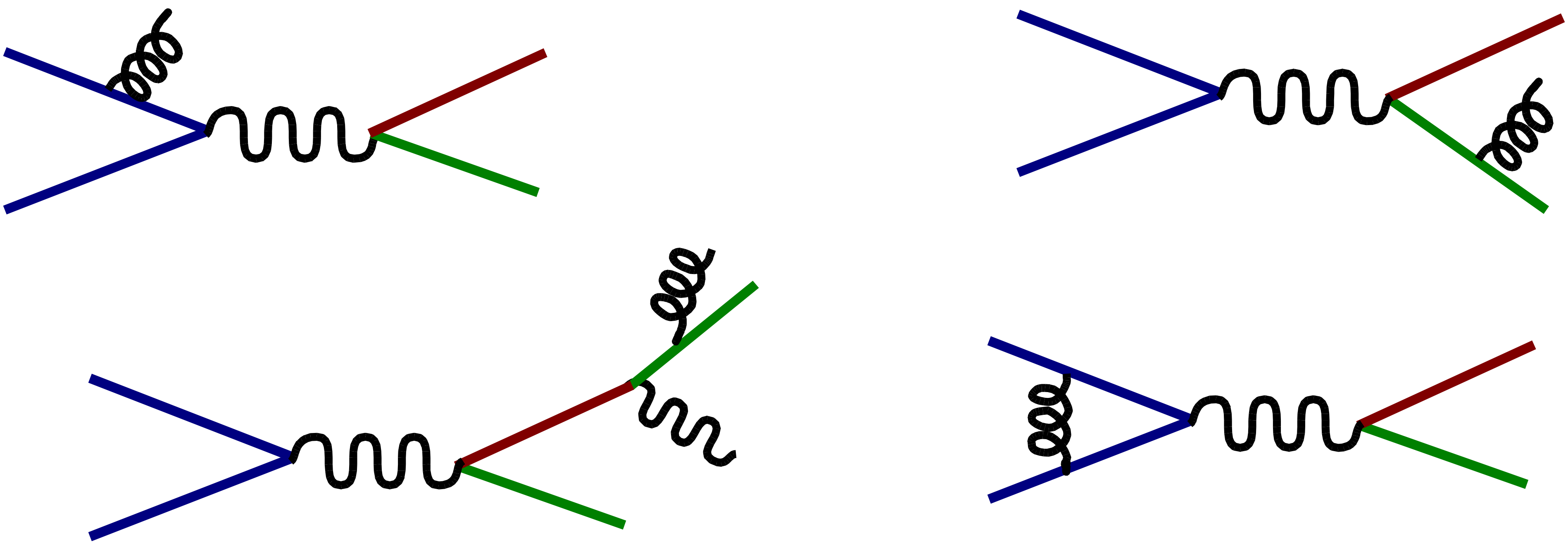


Electroweak Production of Top at the Tevatron

s-channel

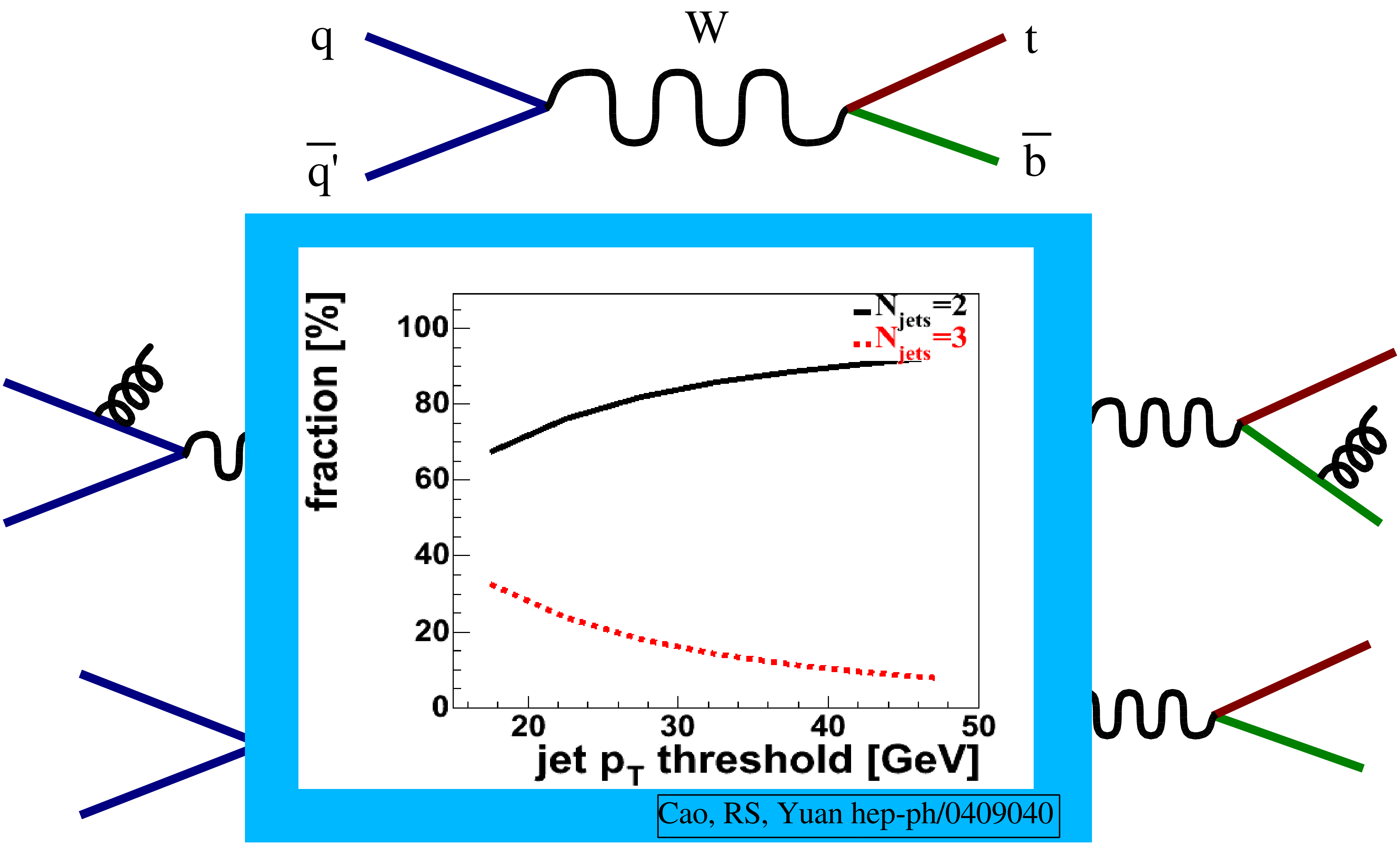


$O(\alpha_s)$ corrections:



Electroweak Production of Top at the Tevatron

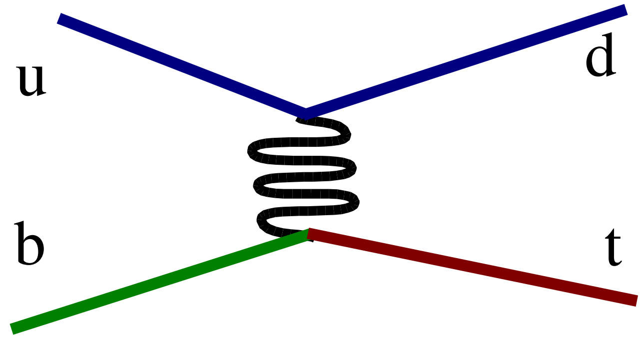
s-channel



Cao, RS, Yuan hep-ph/0409040

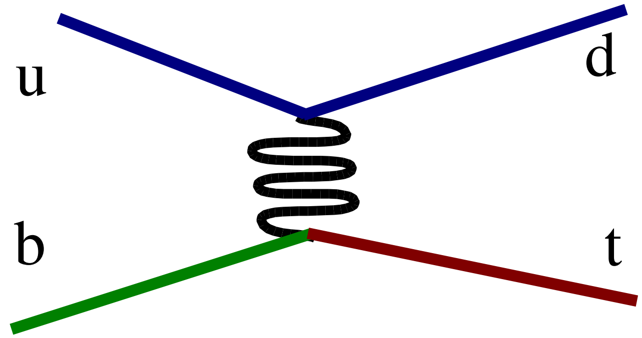
Electroweak Production of Top at the Tevatron

t-channel

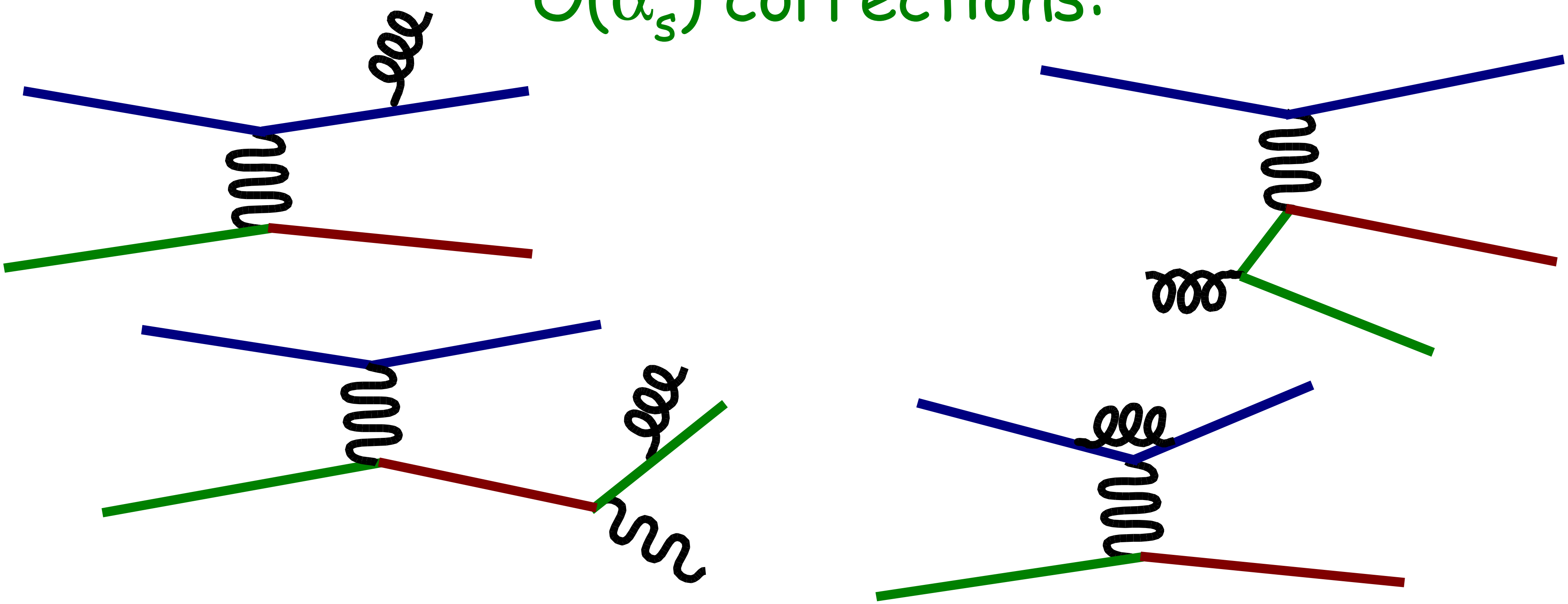


Electroweak Production of Top at the Tevatron

t-channel

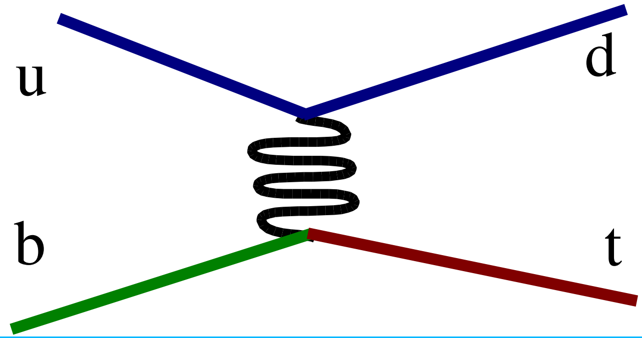


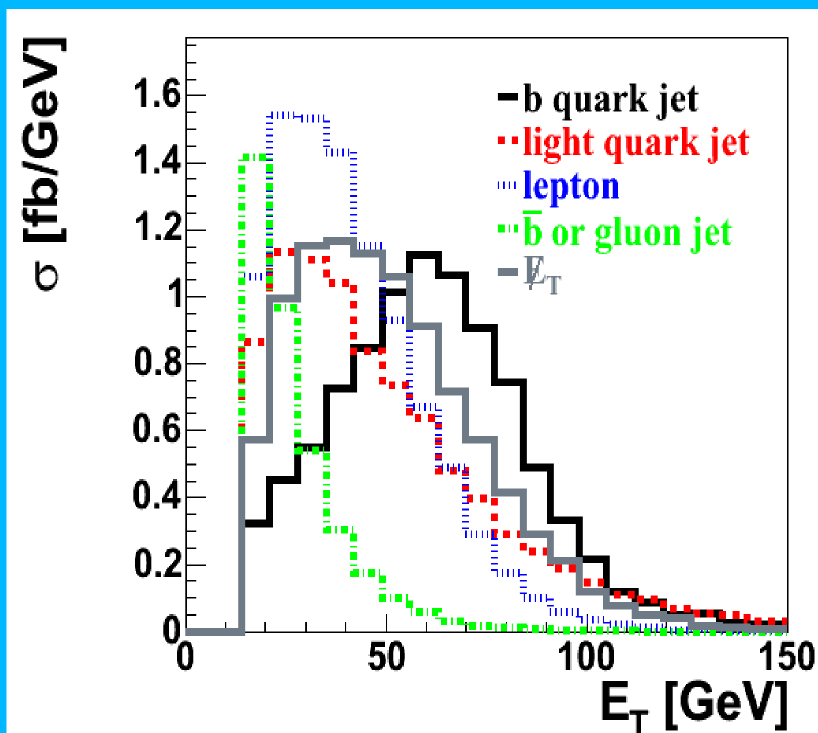
$O(\alpha_s)$ corrections:

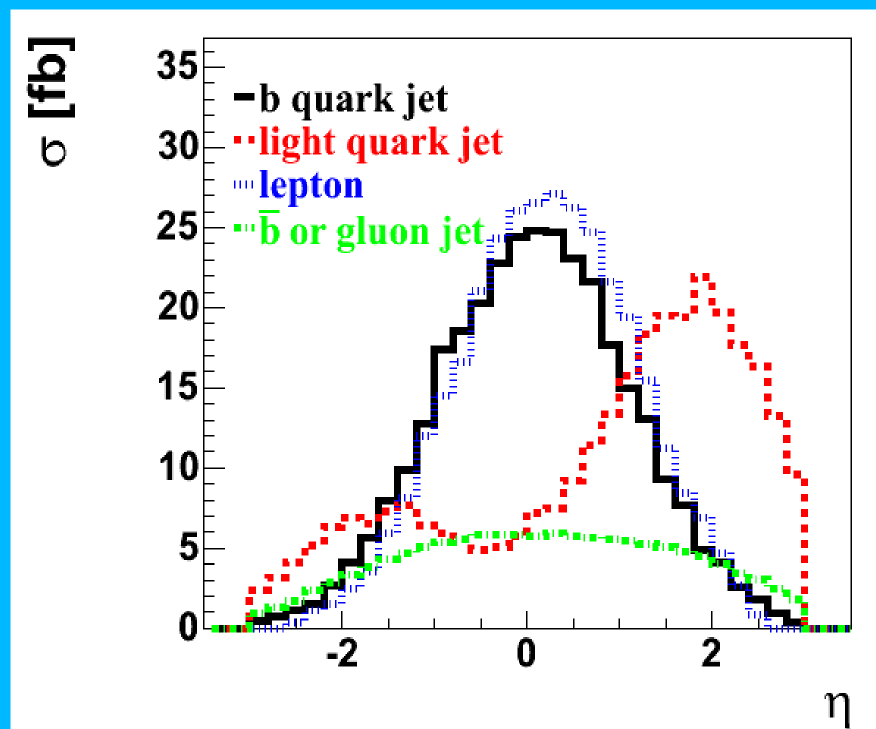


Electroweak Production of Top at the Tevatron

t-channel



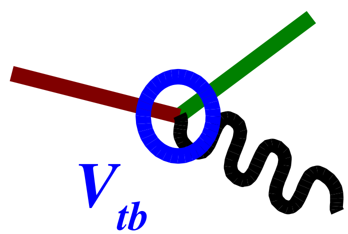




Cao, RS, Benitez, Brock, Yuan hep-ph/0504230

Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$
  - Separately for s-channel and t-channel



CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak interaction eigenstates are not mass eigenstates

Top quark must decay to a *W* plus a *d*, *s*, or *b* quark

$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} = 1 \qquad \rightarrow \qquad V_{tb} > 0.999$$

New physics that couples to the top quark:

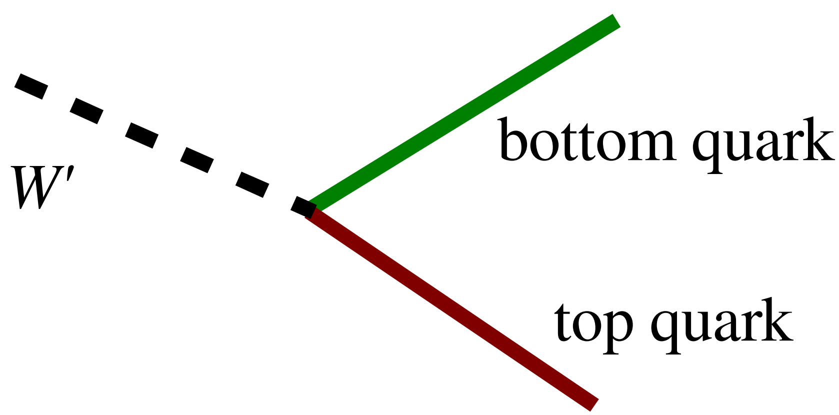
$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} + V_{tx}^{\ 2} = 1$$

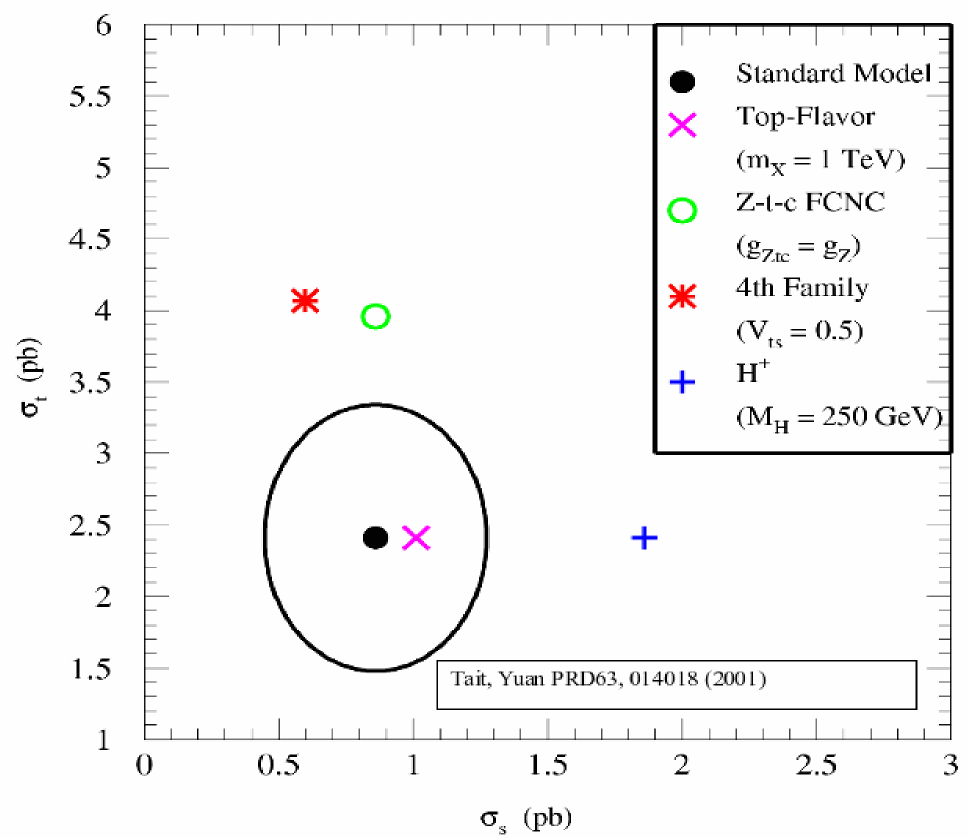
Only weak constraints on V_{tb}

Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections
  - CKM matrix element V_{tb}
- Look for physics beyond the Standard Model
  - Different sensitivity for s-channel and t-channel

Example:Top-Flavor



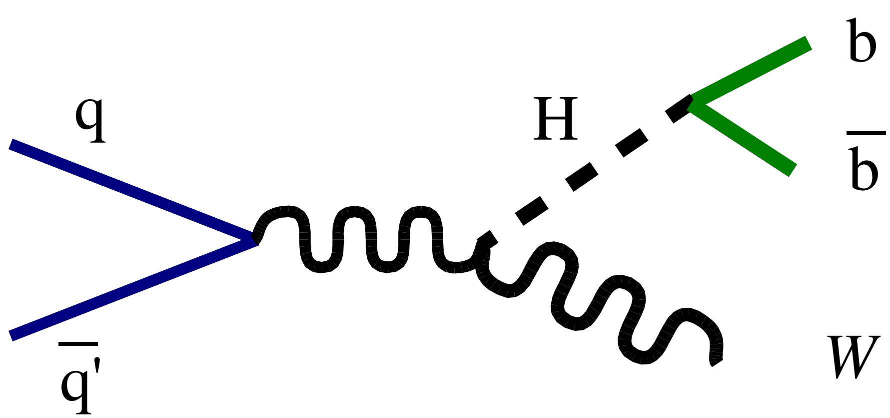


Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections
  - CKM matrix element V_{tb}
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
  - Physics with ~100% polarized top quarks

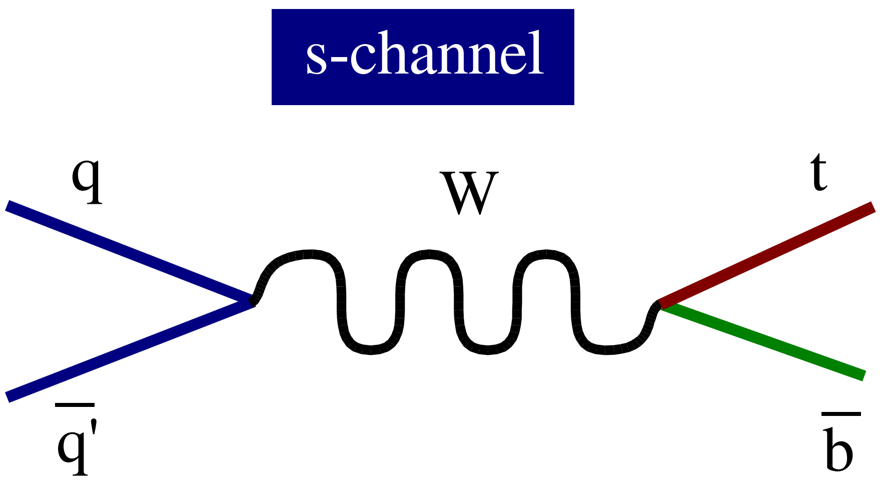
Tevatron Single Top Goals

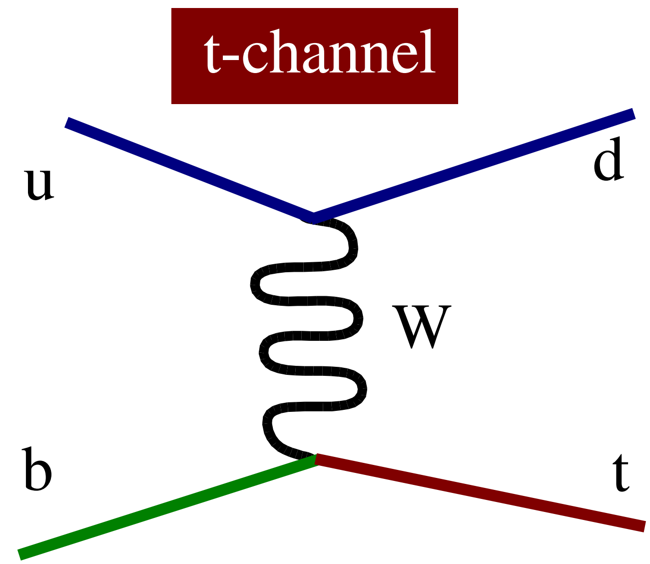
- Observe single top quark production
- Measure production cross sections
  - CKM matrix element V_{tb}
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
- Irreducible background to associated Higgs production



Gateway to the Higgs

Single Top Status

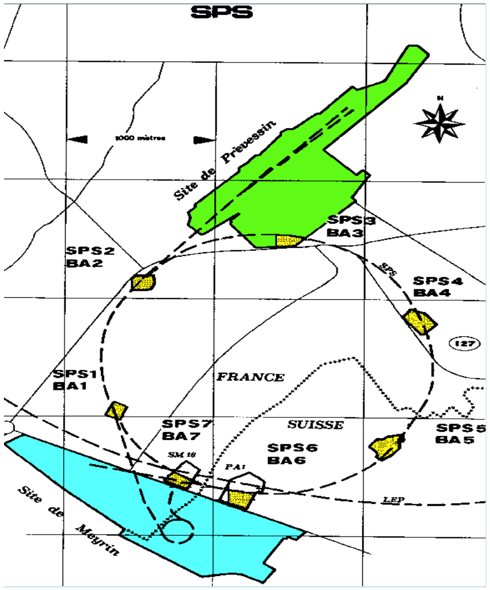


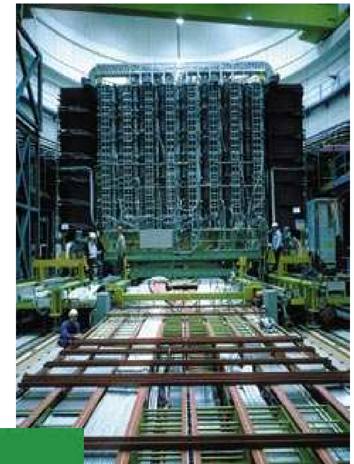


- Production cross section:

	s-channel	*t-channel*	*s+t*
– NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**	
– Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb
– Run II CDF 95% CL limits:	< 14pb	< 10pb	< 18pb

- Other Standard Model production mode (*Wt*) negligible


SPS
1000 mètres
Site de Prévessin
SPS3
BA3
SPS2
BA2
SPS4
BA4
SPS1
BA1
FRANCE
SUISSE
SPS7
BA7
SPS6
BA6
SPS5
BA5
Site de Meyrin
LEP

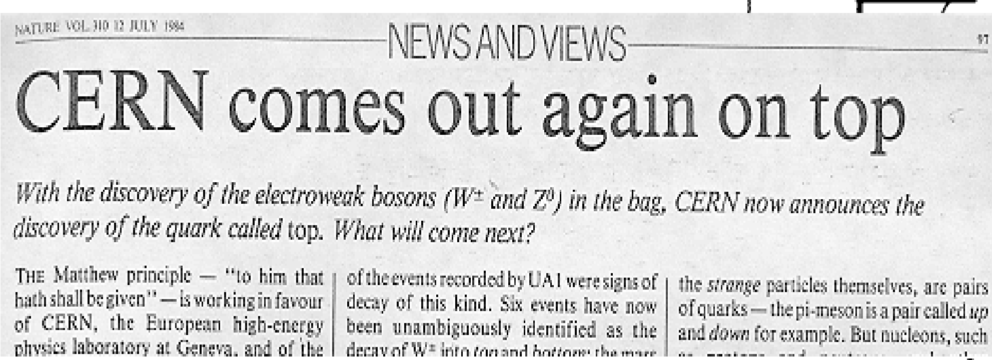



WHERE IN THE
WORLD
is Single Top?


HERA
PETRA

Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
  - SPS: √s=540GeV
- $M_{top} \approx 40$GeV



NATURE VOL 310 12 JULY 1984 — NEWS AND VIEWS — 97

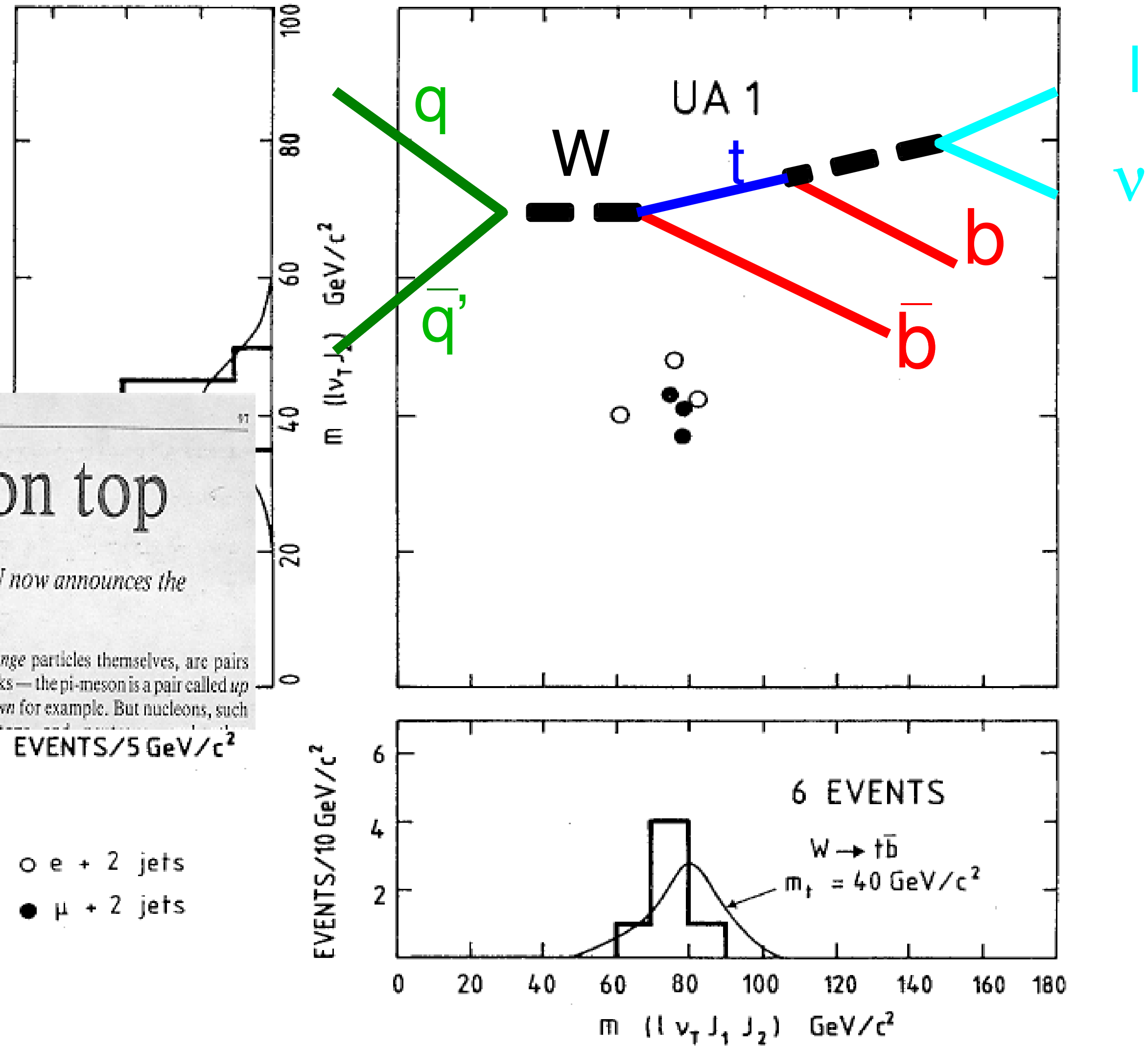
CERN comes out again on top

With the discovery of the electroweak bosons (W± and Z⁰) in the bag, CERN now announces the discovery of the quark called top. *What will come next?*

THE Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the

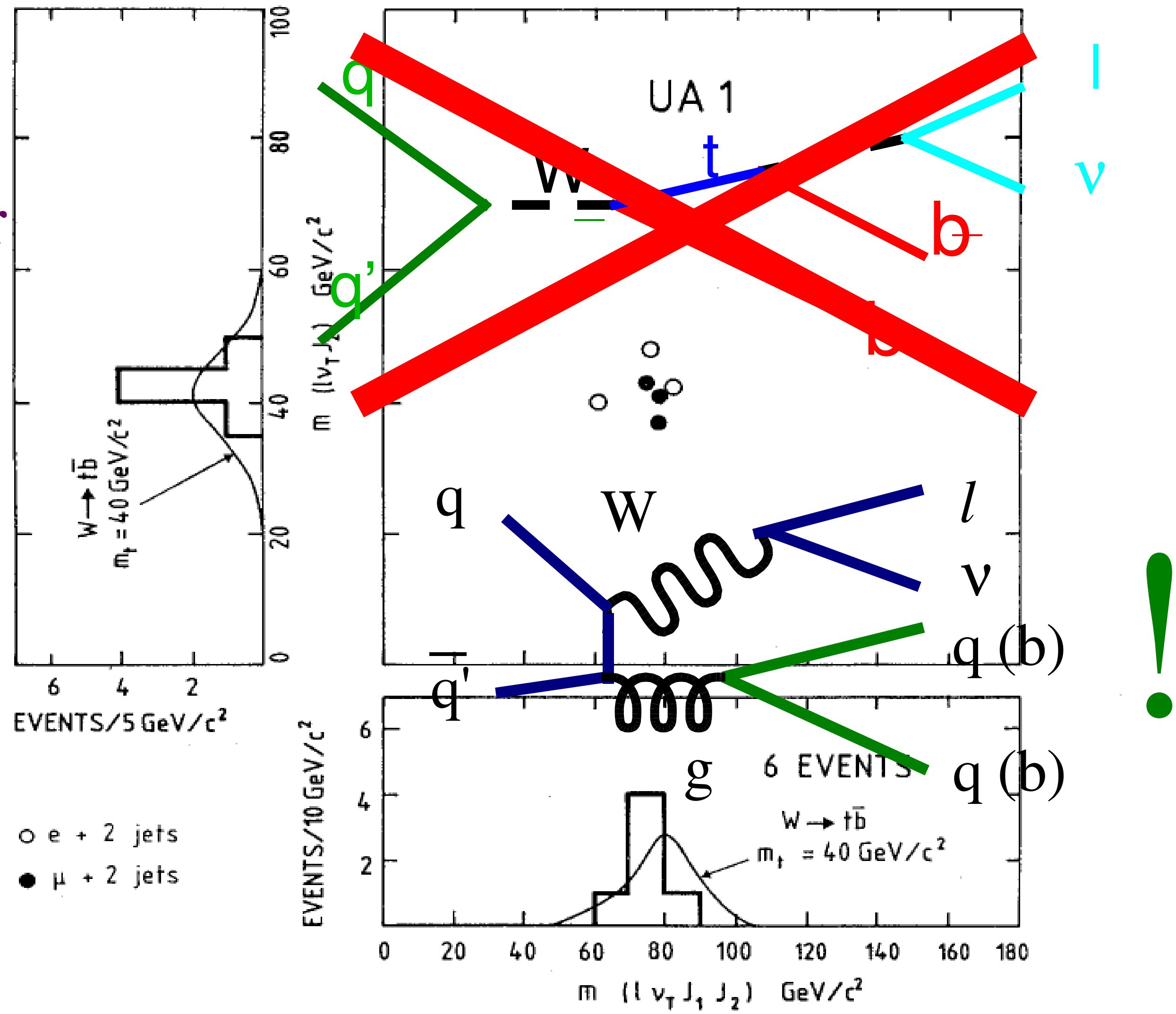
of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the

the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such



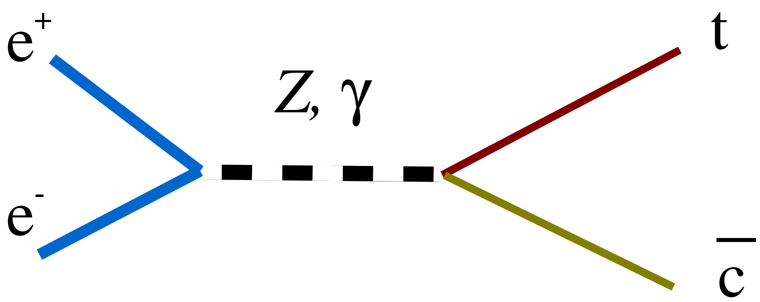
Discovery of Single Top?

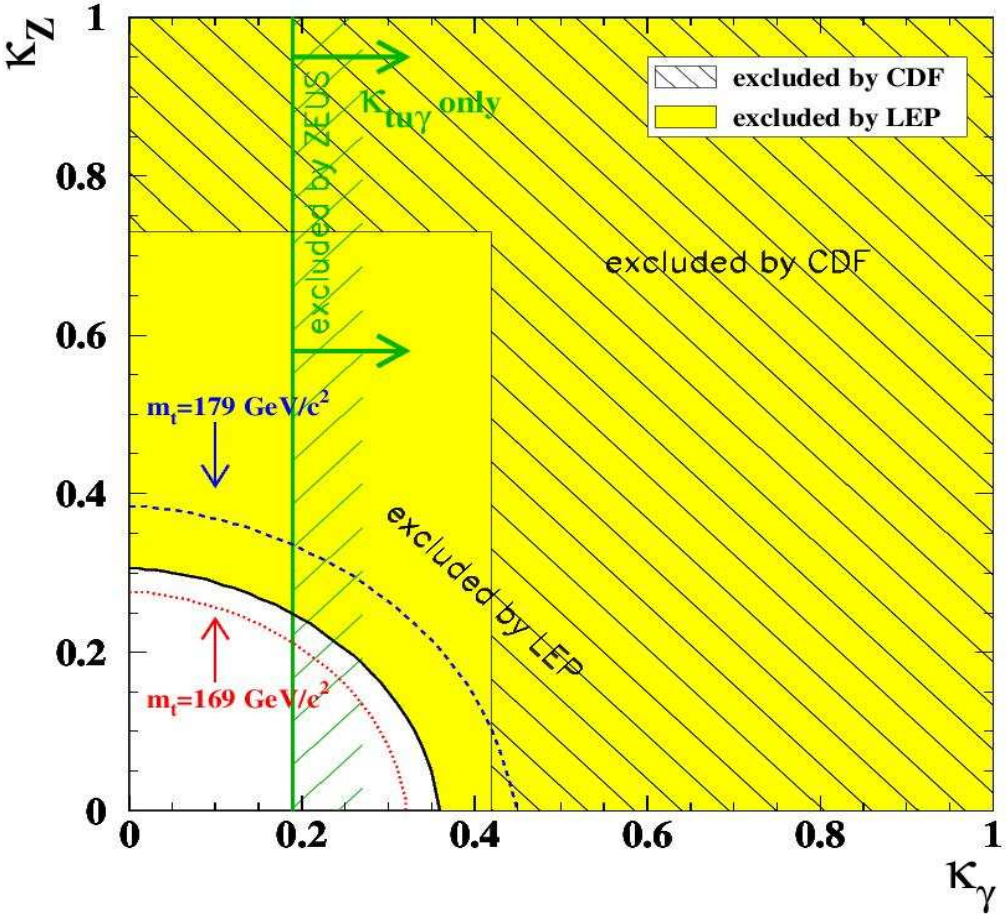
- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{top} \approx 40$GeV
  - Not confirmed after more data and better background estimation
    - W+jets production!



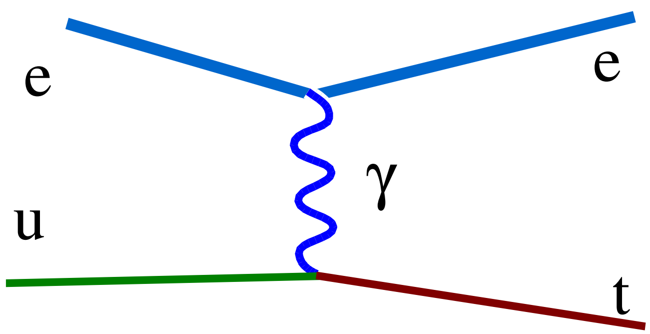
Single Top at LEP and Hera: FCNC

- LEP:
  - $e^+e^- \rightarrow tc$





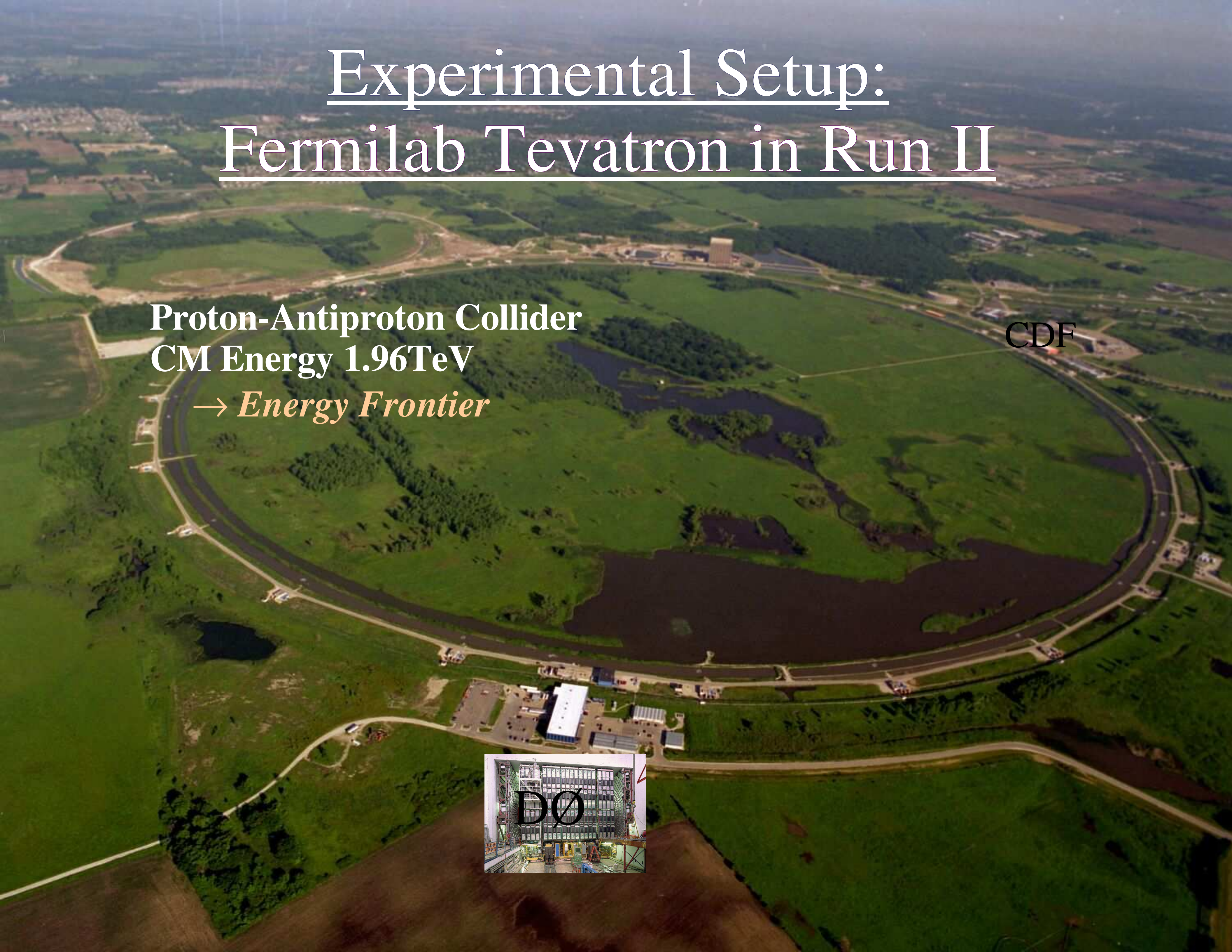
- Hera:
  - $ep \rightarrow et$



Experimental Detection of Single Top Events

Experimental Setup: Fermilab Tevatron in Run II

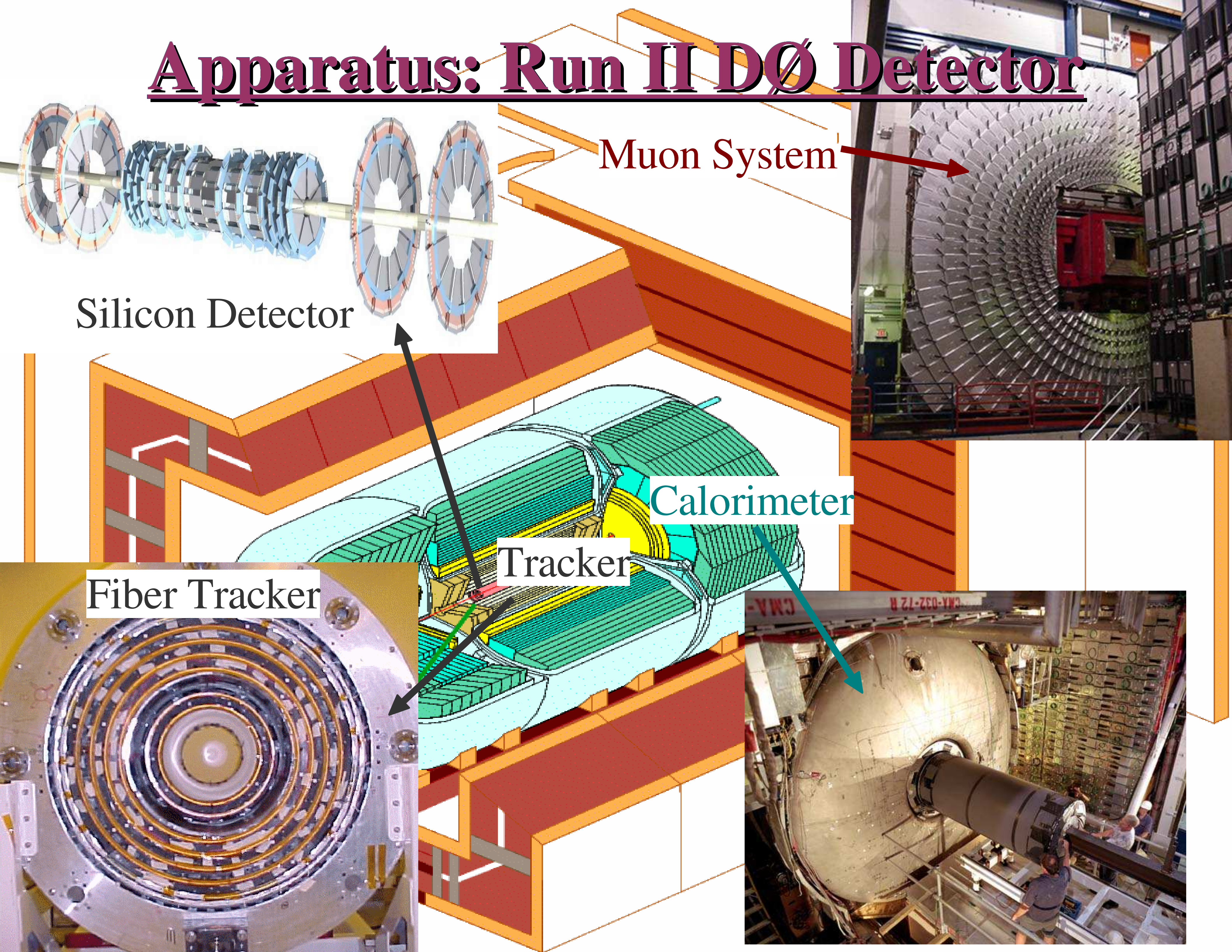
Proton-Antiproton Collider
CM Energy 1.96TeV
→ ***Energy Frontier***

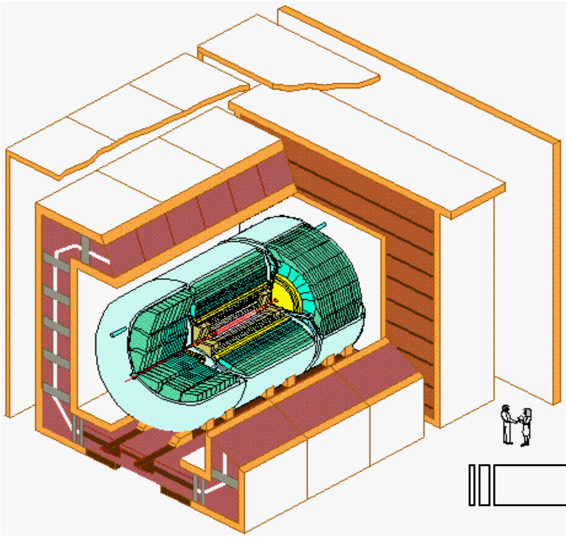


Experimenters

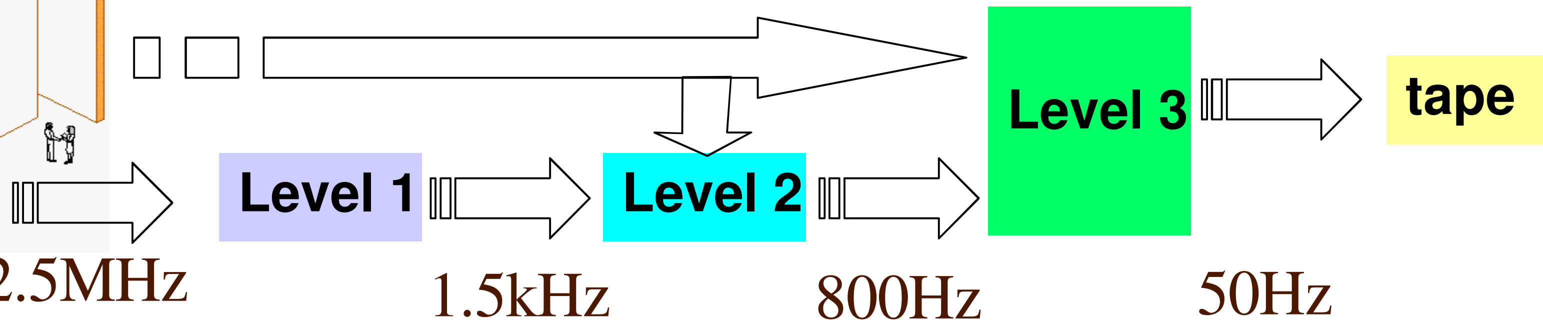
- 19 countries
- 80 institutions
- 670 physicists

Apparatus: Run II DØ Detector



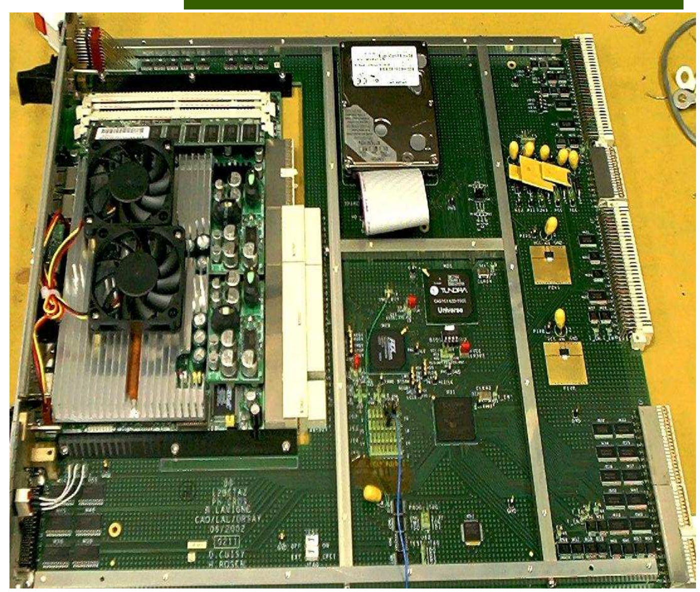


Collecting Data: Triggering

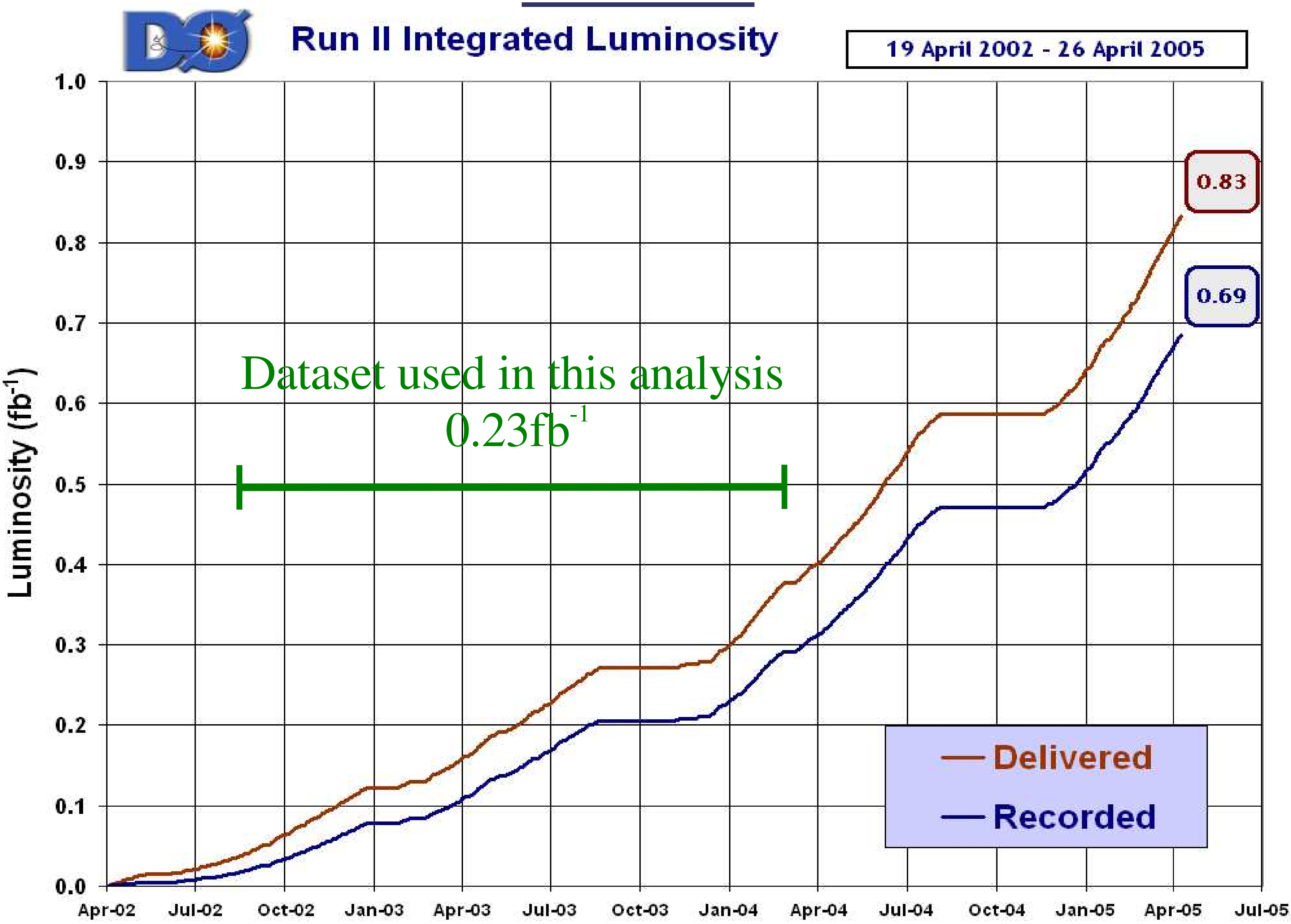


- Multi-level, pipelined, buffered Trigger Strategy
  - Level 1: one interaction every 396ns
    - Fast trigger pick-offs from all detectors
    - Trigger on hit patters in individual detector elements
  - Level 2: Combine Level 1 regions and objects
    - Custom dataflow hardware/firmware
    - Event reconstruction on Pentium CPUs
  - Level 3: Full detector readout
    - Complete event reconstruction on Linux processor farm

L2 Processor Board



Dataset

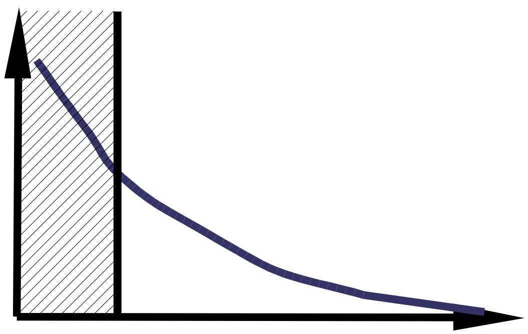


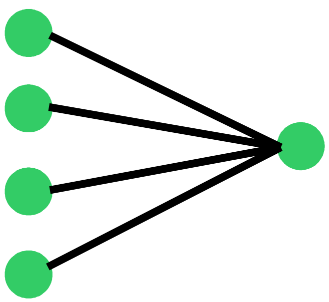
Run II Integrated Luminosity
19 April 2002 - 26 April 2005
Luminosity (fb^{-1})
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
0.83
0.69
Dataset used in this analysis
0.23fb^{-1}
Delivered
Recorded

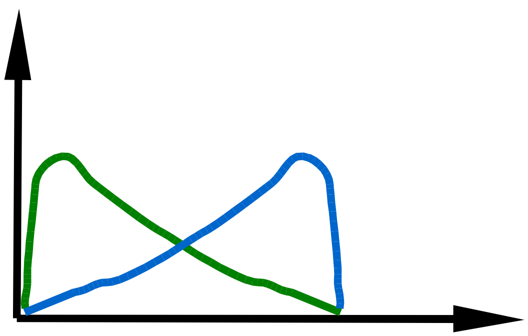
Analysis Outline

Goal:

Maximize Sensitivity



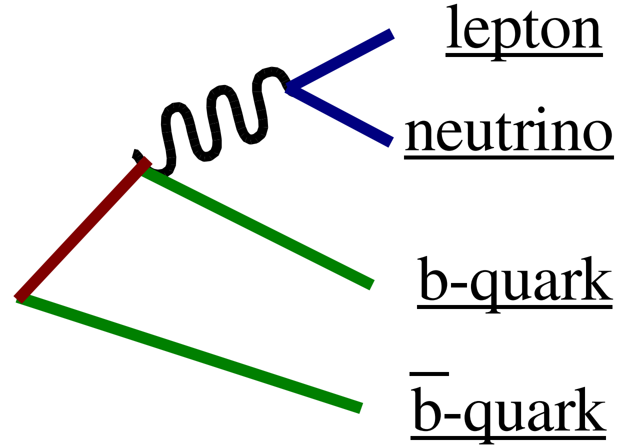




1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Separate signal from backgrounds
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting
   - Binned likelihood

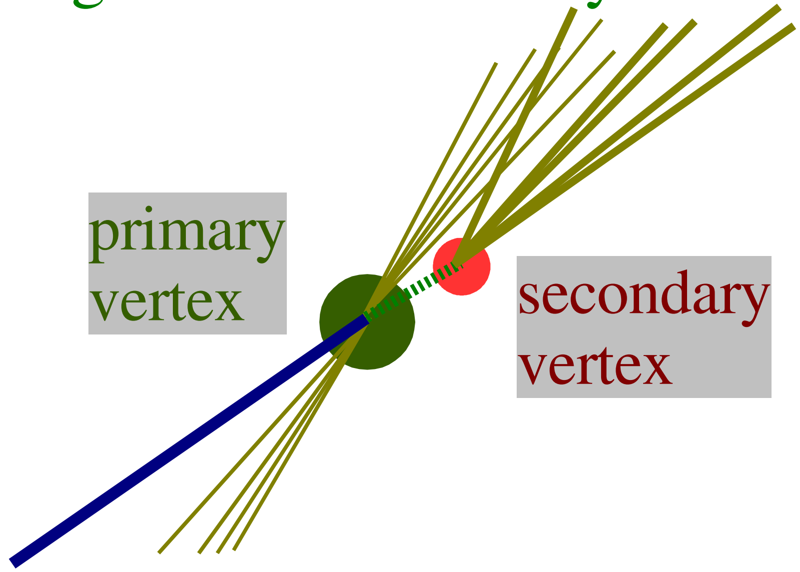
Event Selection

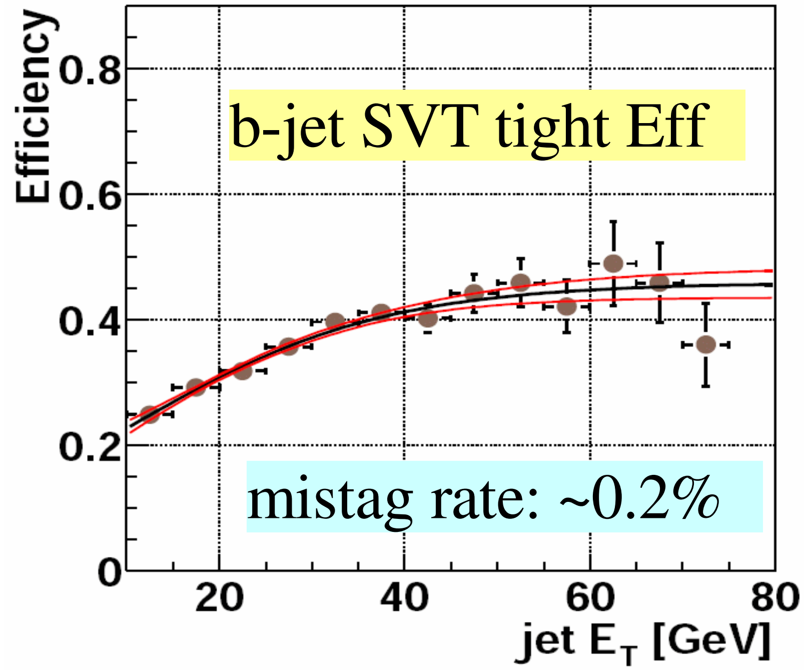
- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15$GeV, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15$GeV, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15$GeV
- Jets:
  - $p_T > 15$GeV, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV
  - $2 \leq n_{jets} \leq 4$
- Reject mis-reconstructed events



Event Selection: b-tagging

Algorithm: Secondary Vertex Tag





s-channel

- Final state:
  - 2 high-p_T b-jets

➔ Require ≥1 b-tagged jet

t-channel

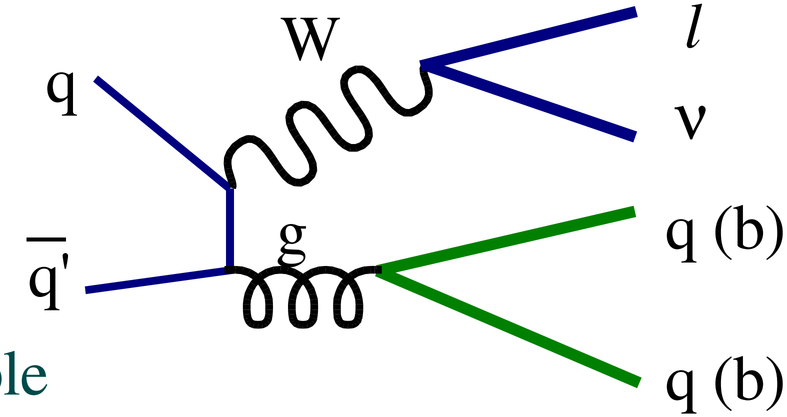
- Final state:
  - 1 high-p_T b-jet
  - 1 high-p_T light quark jet

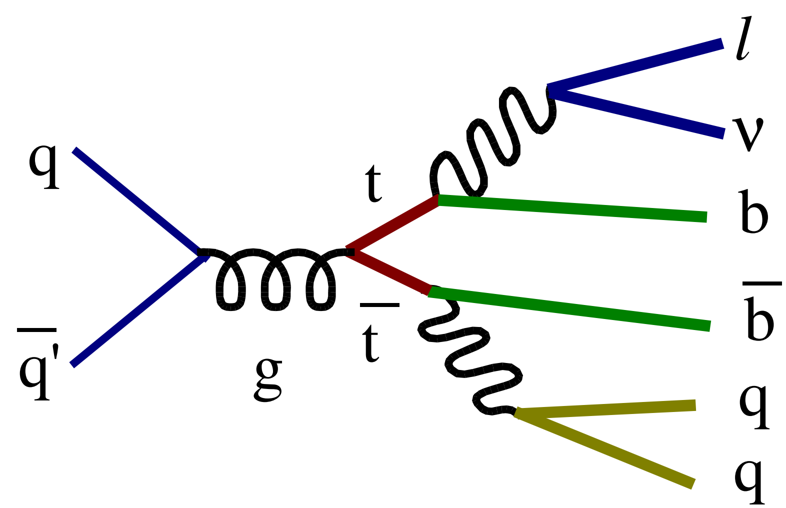
➔ Require ≥1 b-tagged jet

➔ Require ≥1 untagged jet

Background Modeling

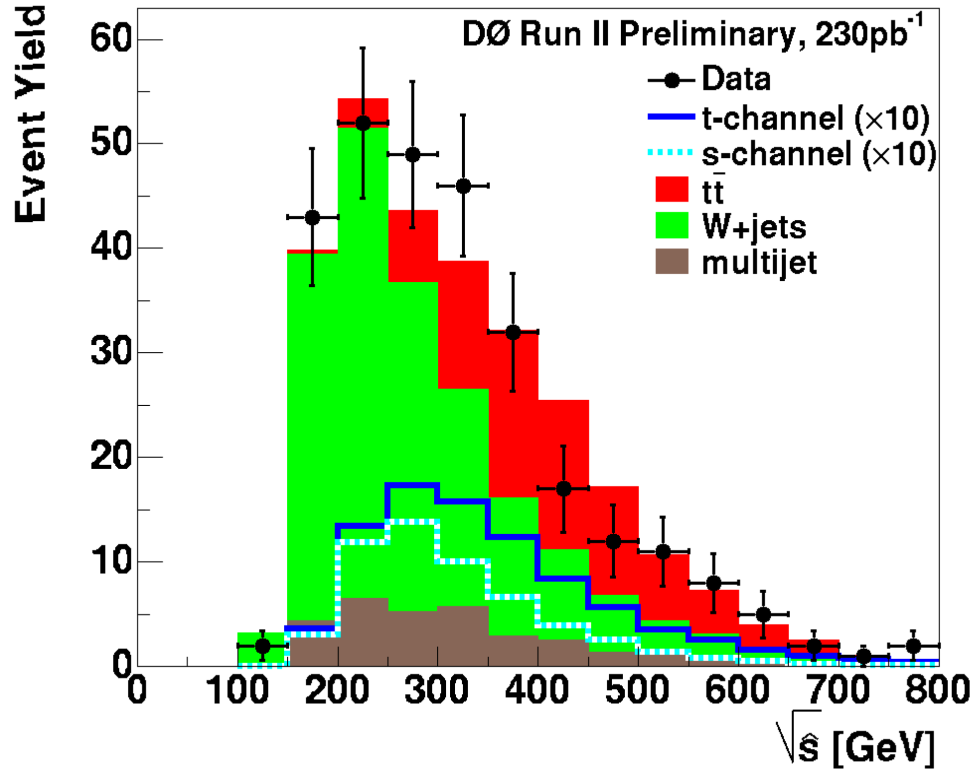
- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO
- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC





Event Yield

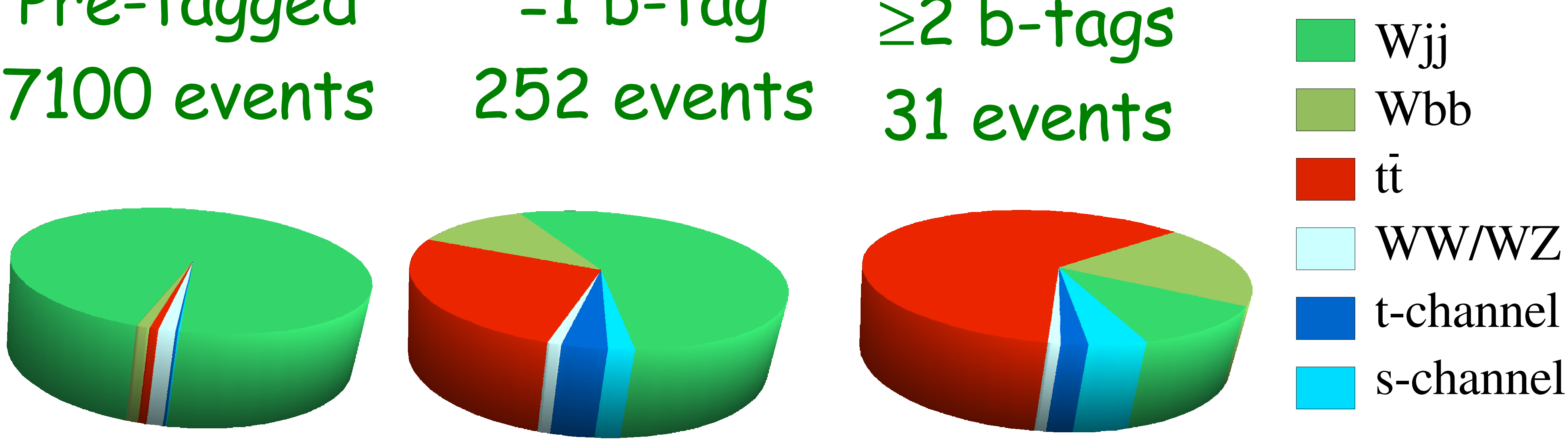
	s-channel	t-channel
Cut acceptance	23%	22%
b-tag efficiency	54%	38%
Signal yield	5.5	8.5
BKgnd yield	287	276
Signal/bkgnd	1:52	1:32



Pre-tagged
7100 events

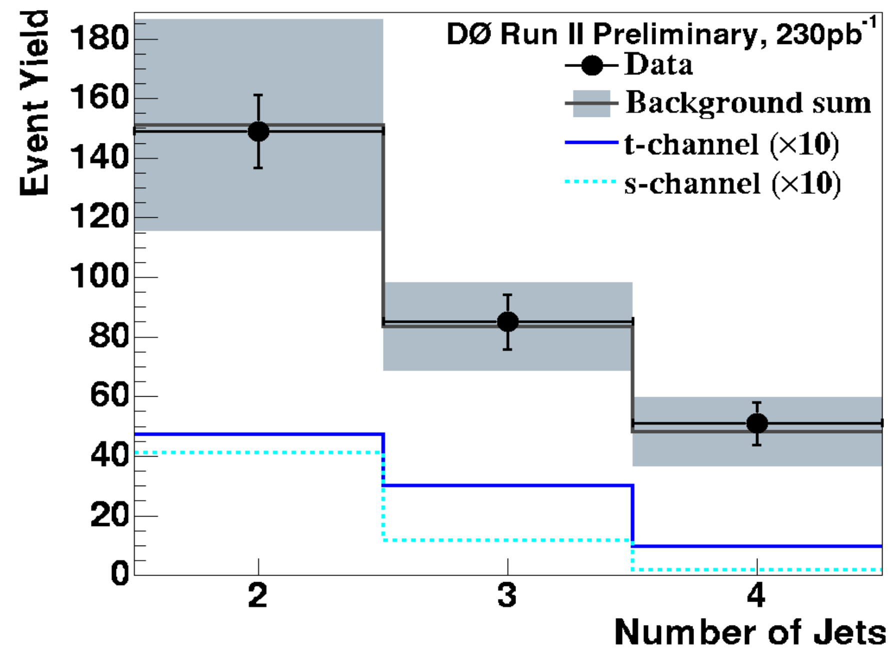
=1 b-tag
252 events

≥2 b-tags
31 events



Systematic Uncertainties

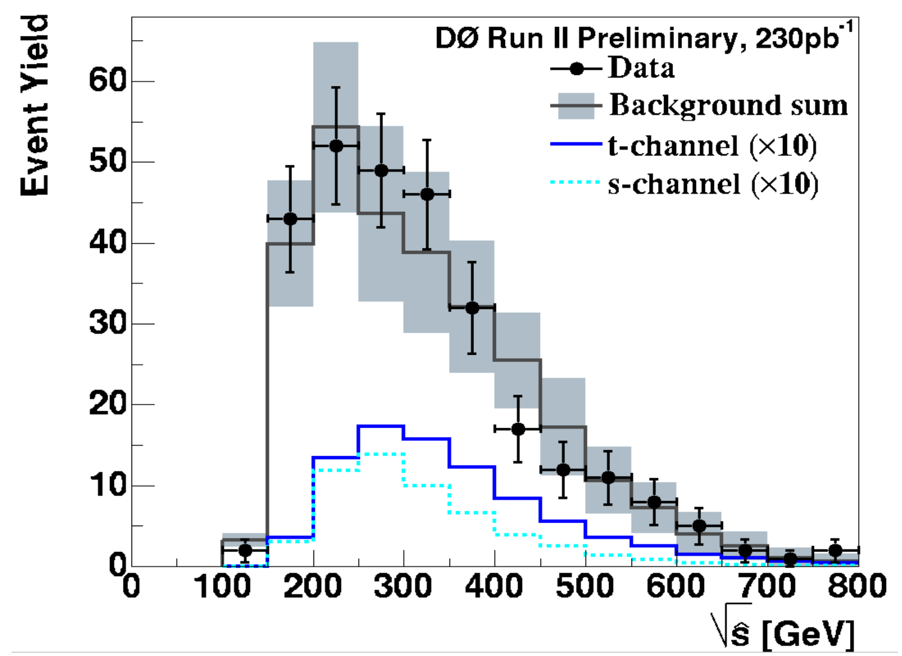
Monte Carlo Systematic Uncertainties	
Theory cross sections	15 %
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet Fragmentation	6 %
Jet ID	5 %
ℓ ID	5 %



- Some uncertainties also affect shape
  - JES, b-tag and trigger modeling
- Total Uncertainty

	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

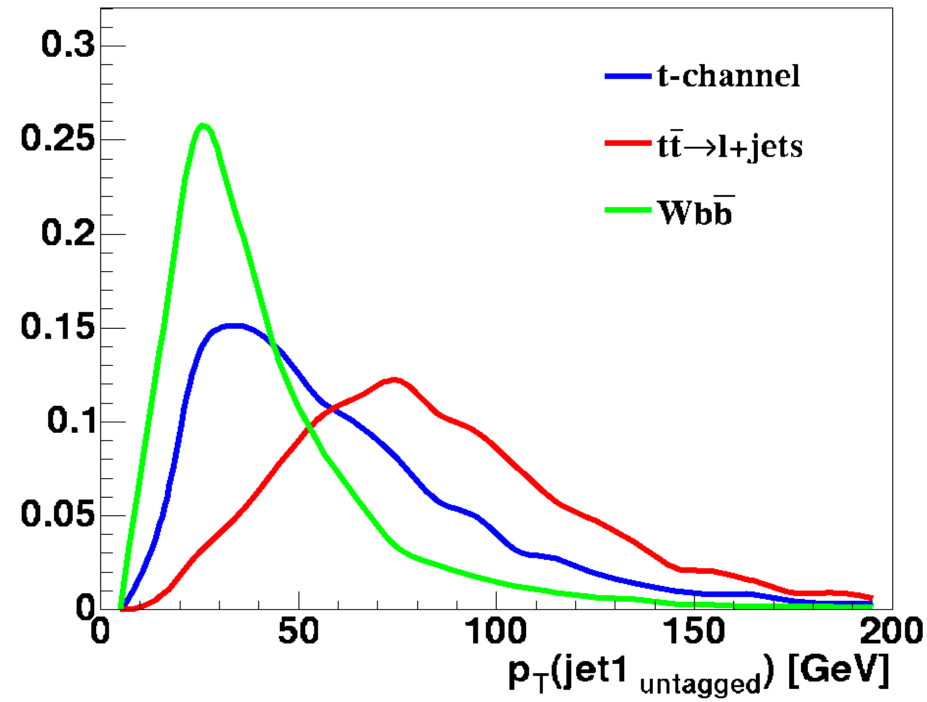
Result is statistics limited

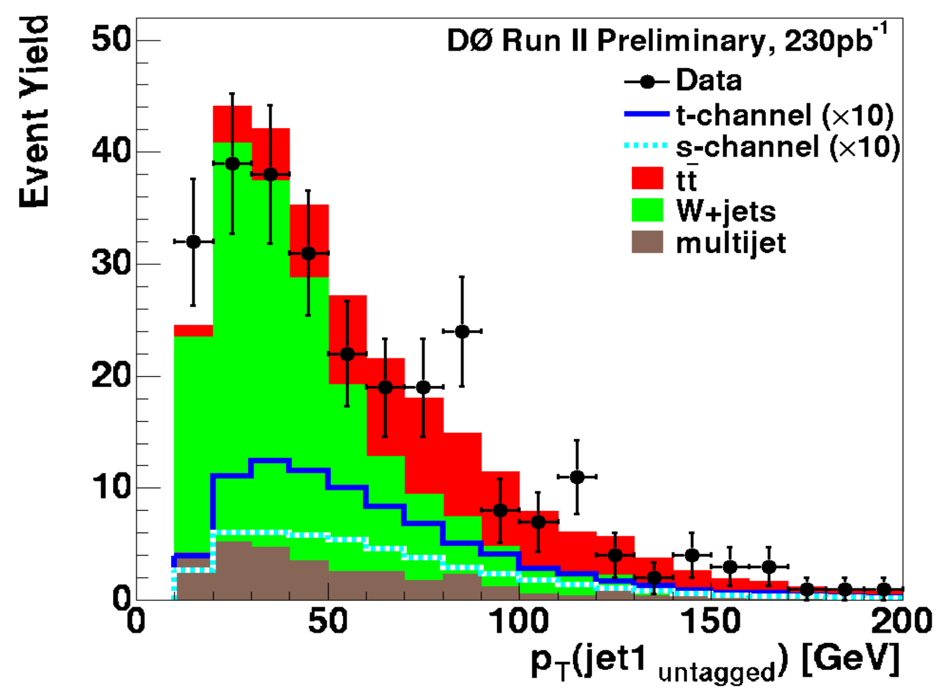


A Treasure Chest of Discriminating Variables

Object p_T

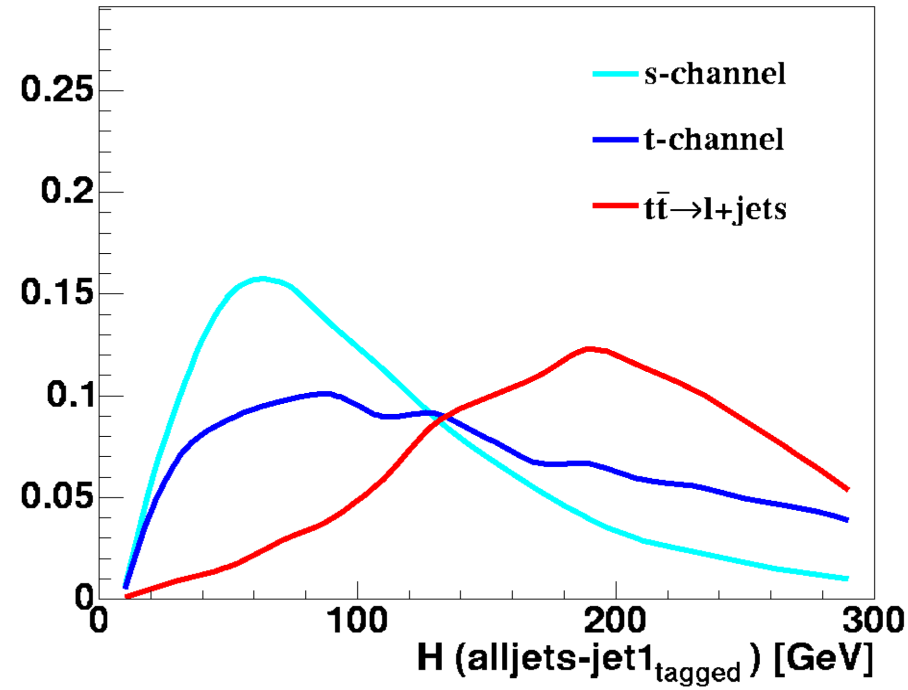
- p_T of jets:
  - Both s-channel and t-channel:
    - $\text{Jet1}_{\text{tagged}}$
  - Only t-channel:
    - $\text{Jet 1}_{\text{untagged}}$
    - $\text{Jet 2}_{\text{untagged}}$
  - Only s-channel:
    - $\text{Jet 1}_{\text{non-best}}$
    - $\text{Jet 2}_{\text{non-best}}$

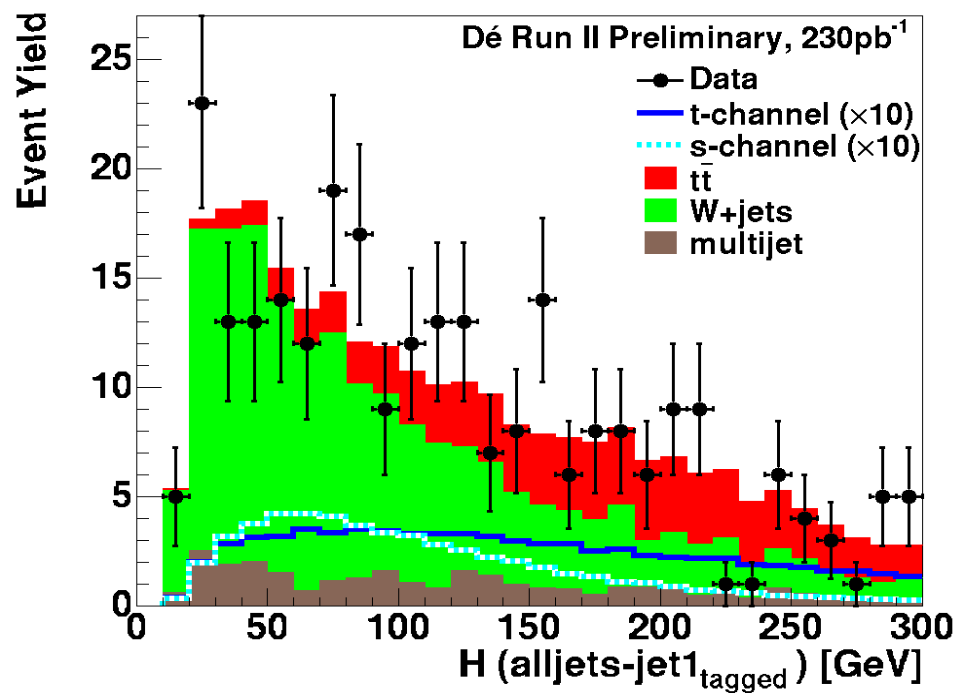




Event Energy

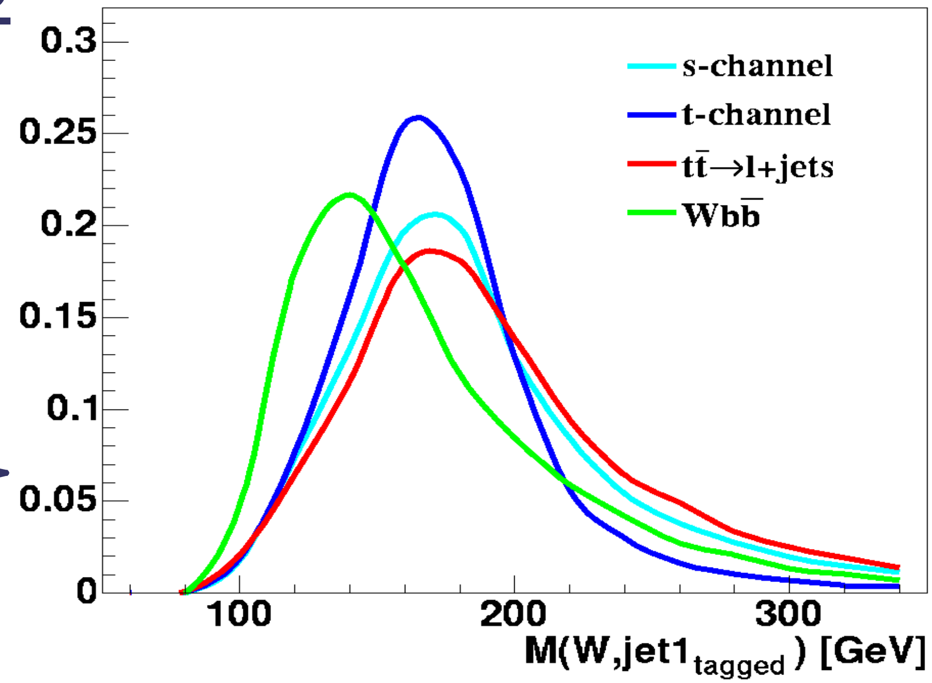
- Total energy $H = \Sigma_i E^i$
  transverse energy $H_T = \Sigma_i E^i_T$
  - Both s-channel and t-channel:
    - H(all jets – $\text{Jet1}_{\text{tagged}}$)
  - Only t-channel:
    - H_T(all jets)
    - H_T(all jets – $\text{Jet1}_{\text{tagged}}$)
  - Only s-channel:
    - H(all jets – Jet_{best})
    - H_T(all jets – Jet_{best})

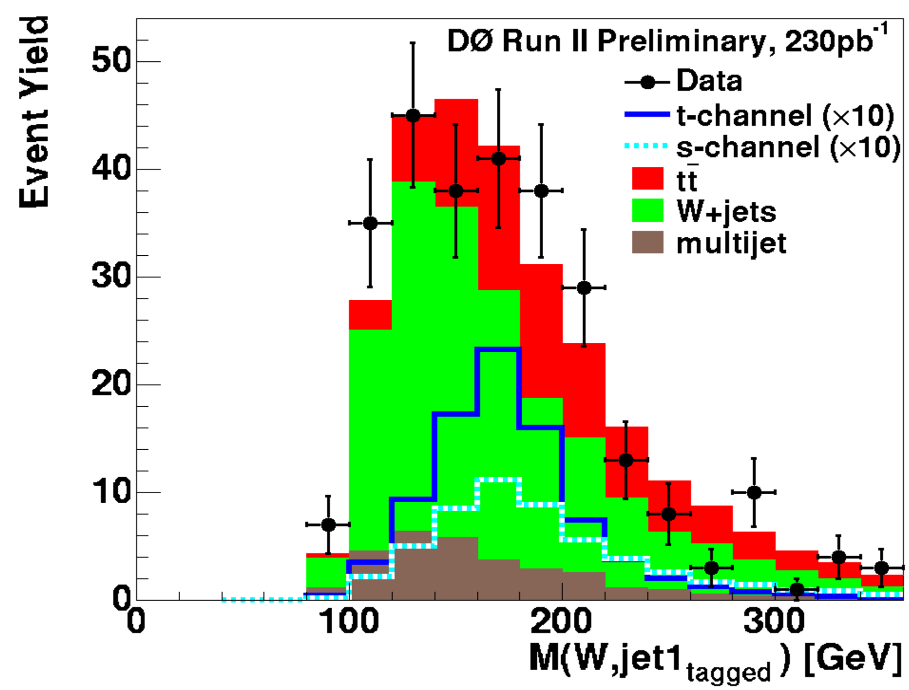




Reconstructed Objects

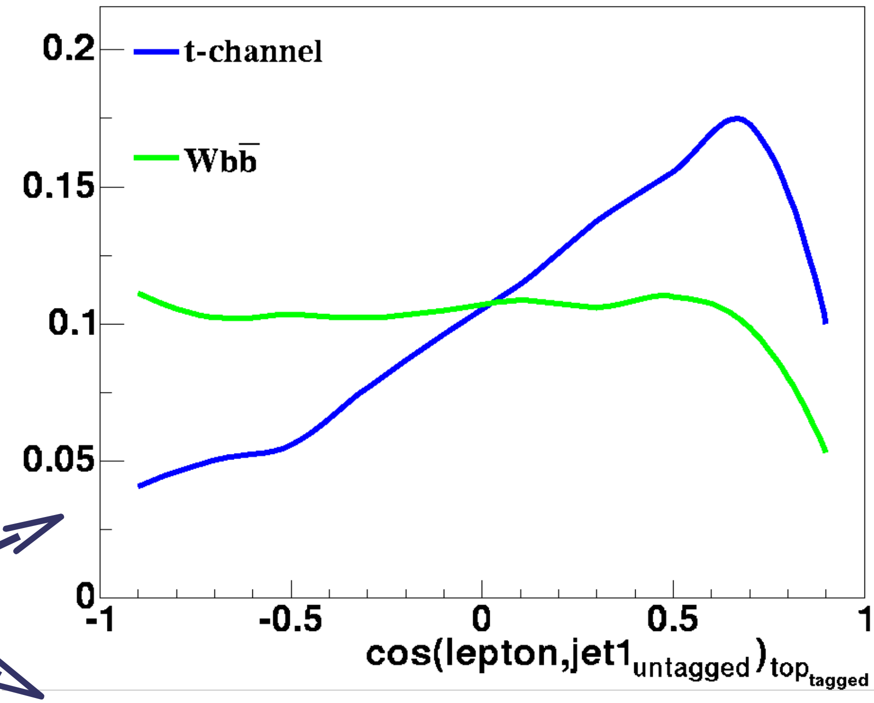
- Both s-channel and t-channel:
  - M(all jets)
  - p_T(all jets – $\text{Jet1}_{\text{tagged}}$)
  - $M(\text{top}_{\text{tagged}})$
  - $\sqrt{\hat{s}}$
- Only t-channel:
  - M(all jets – $\text{Jet1}_{\text{tagged}}$)
- Only s-channel:
  - M_T(Jet1, Jet2)
  - p_T(Jet1, Jet2)
  - M(all jets – $\text{Jet1}_{\text{best}}$)
  - $M(\text{top}_{\text{best}})$

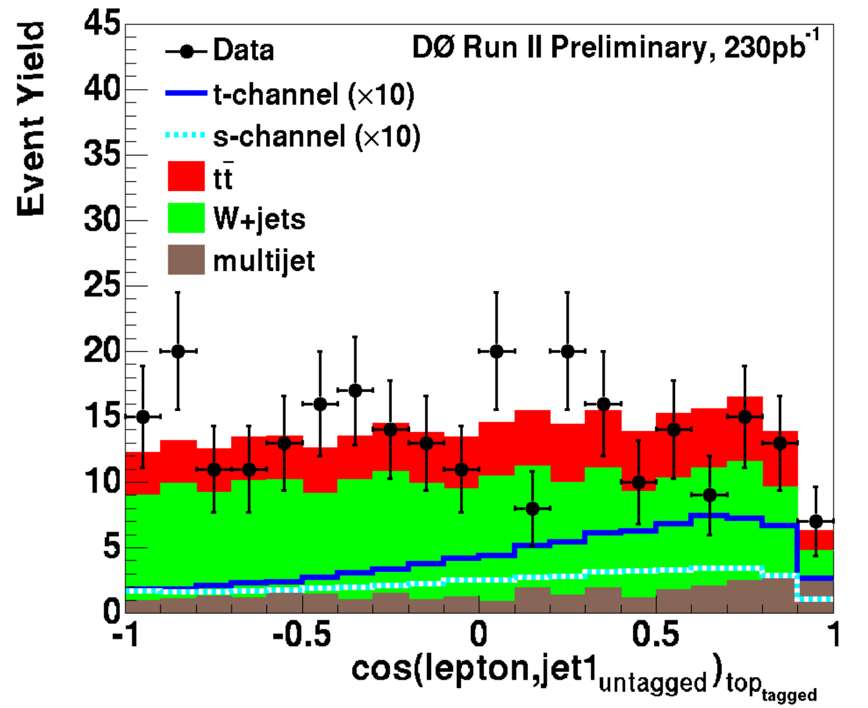




Angular Correlations

- Both s-channel and t-channel:
  - ΔR(Jet1, Jet2)
- Only t-channel:
  - $\eta(\text{Jet1}_{\text{untagged}}) \times Q(\text{lepton})$
  - $\cos(\text{lepton}, \text{Jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet1}_{\text{tagged}})_{\text{all jets}}$
- Only s-channel:
  - $\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet1}_{\text{non-best}})_{\text{all jets}}$

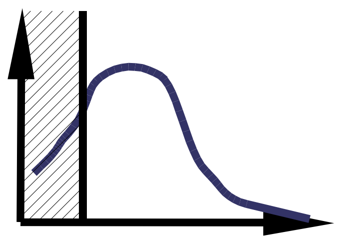


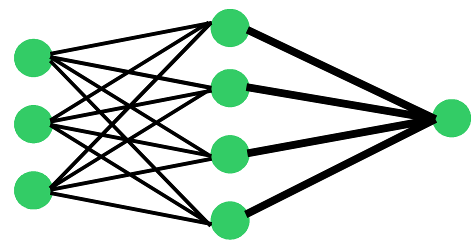


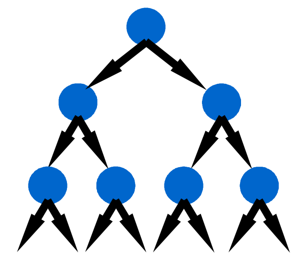
Separating Signal from Backgrounds

- Three analysis methods

Cut-Based — Neural Networks — Decision Trees

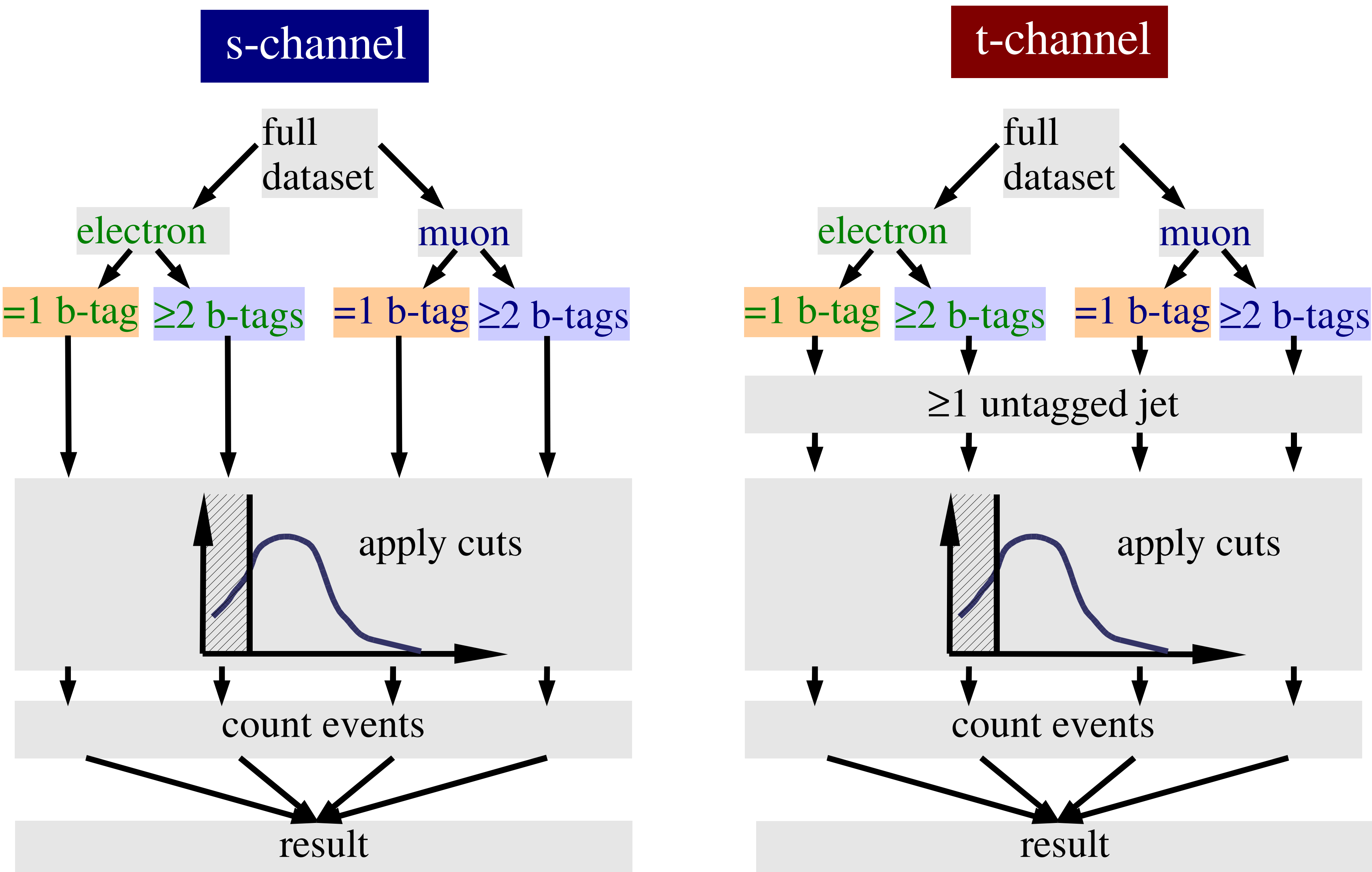






- Each using the same structure:
  - – Optimize separately for s-channel and t-channel
    - Optimize separately for electron and muon channel (same variables)
  - – Focus on dominant backgrounds: W+jets, tt
    - W+jets – train on tb-Wbb and tqb-Wbb
    - tt – train on tb – $tt \rightarrow l + \text{jets}$ and tqb – $tt \rightarrow l + \text{jets}$
  - – Based on same set of discriminating variables
  - → 8 separate sets of cuts/networks/trees

1. Cut-Based Analysis



1. Cut-Based Analysis

- Cuts on sensitive variables to isolate single top
  - Optimize s-channel and t-channel searches separately
  - Loose cuts on energy-related variables:

$p_T(\text{jet1}_{\text{tagged}})$

$H(\text{alljets} - \text{jet1}_{\text{tagged}})$

$H(\text{alljets} - \text{jet1}_{\text{best}})$

$H_T(\text{alljets})$

$M(\text{top}_{\text{tagged}})$

$M(\text{alljets})$

$M(\text{alljets} - \text{jet1}_{\text{tagged}})$

$\sqrt{\hat{s}}$

Event Yields

	s-channel search	t-channel search
s-channel signal	$\boxed{4.5}$	3.2
t-channel signal	5.5	$\boxed{7}$
W+jets	103	73
top pairs	28	56
multijet	17	17
Background sum	153±25	149±25
Observed	152	148
Signal/Bkgnd	1:34	1:21

Result

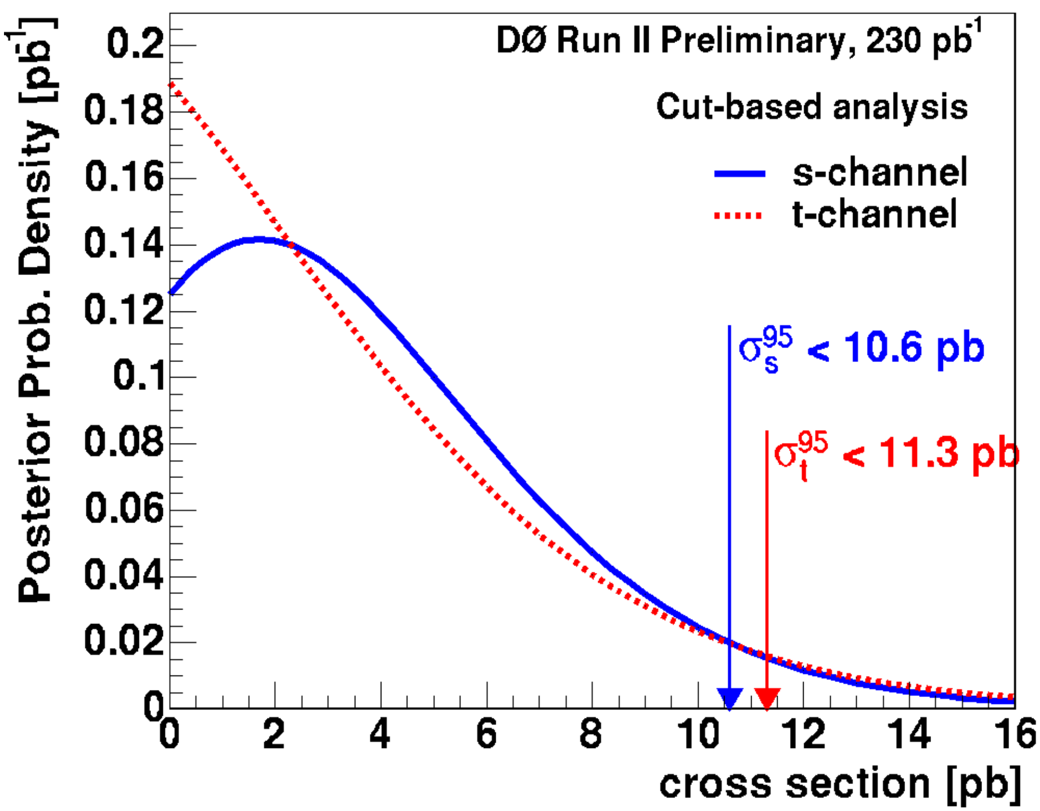
- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limit
  - – Using Bayesian approach
  - – Combine all analysis channels (e, μ, =1 tag, ≥2 tags)
  - – Take systematics and correlations into account

Expected limit: set N_{obs} to background yield

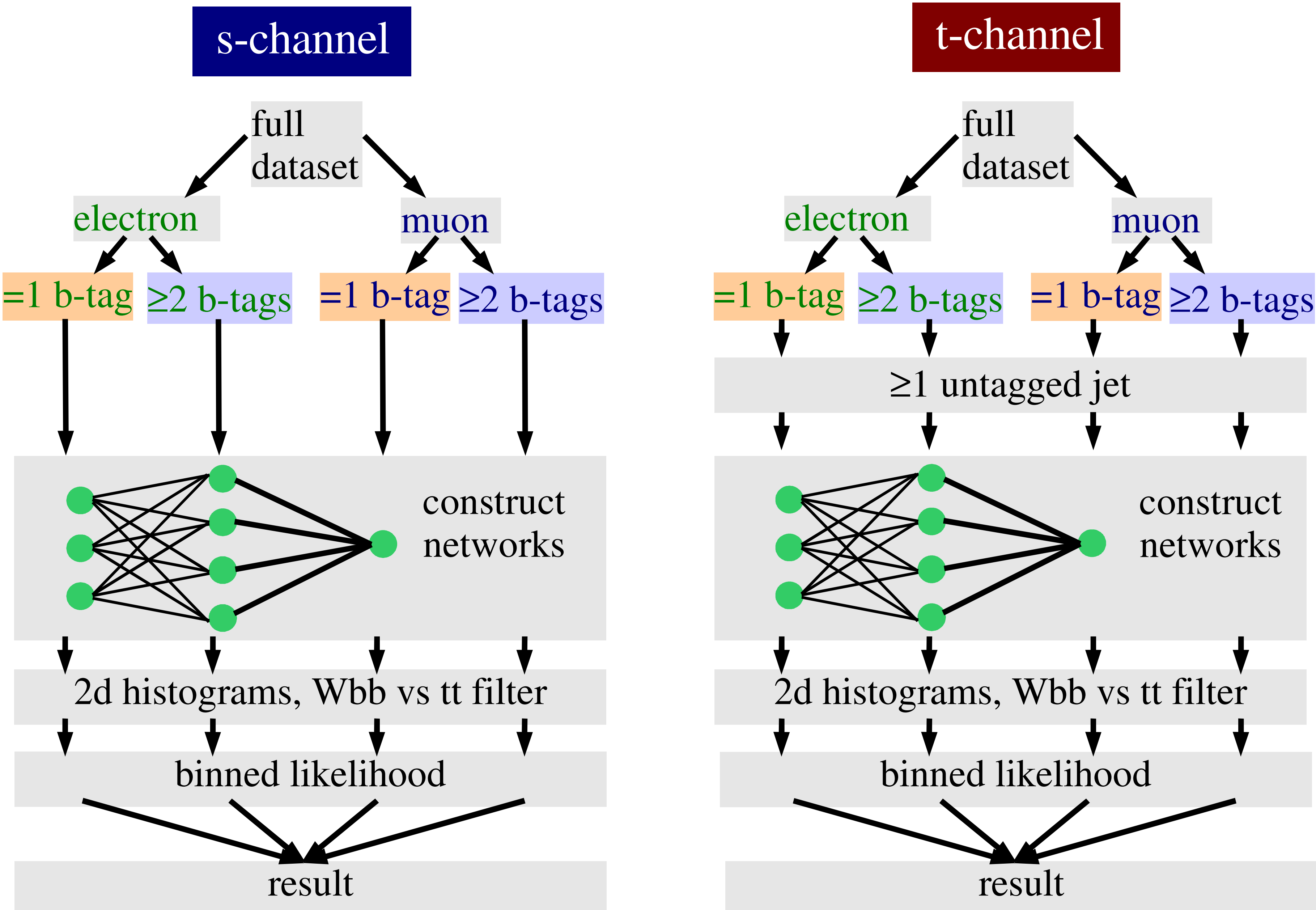
Expected/Observed limit:

$\sigma_s <$ 9.8 / 10.6 pb

$\sigma_t <$ 12.4 / 11.3 pb

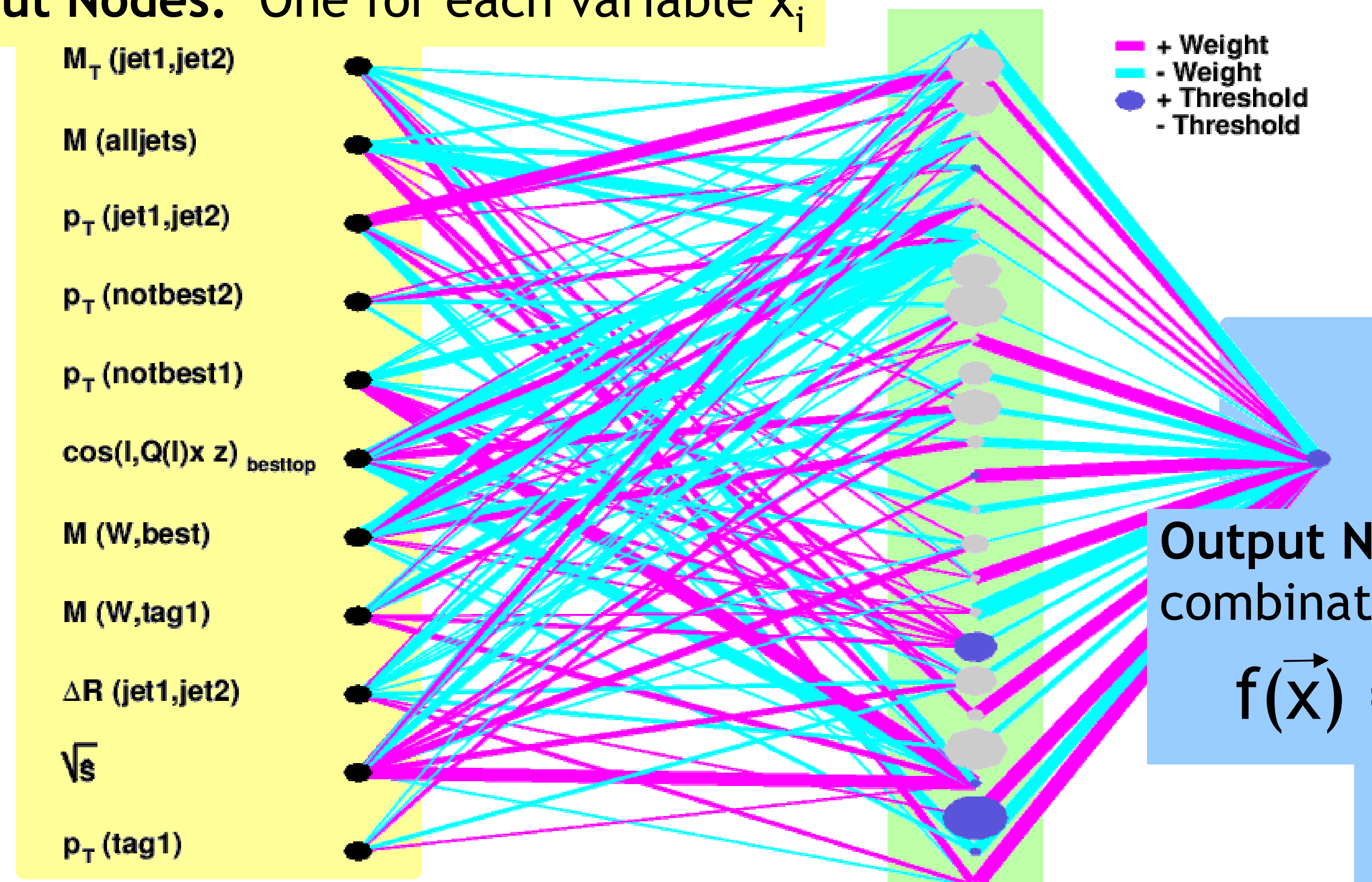


2. Neural Network Analysis



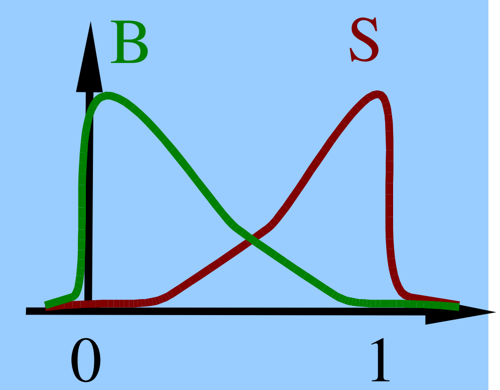
Neural Networks

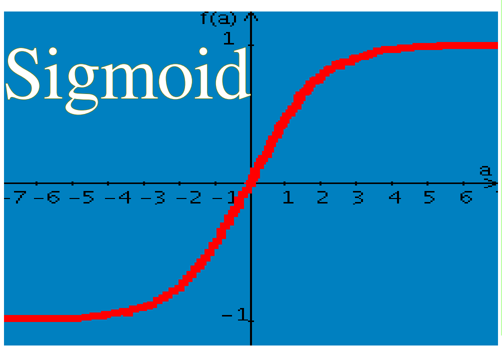
Input Nodes: One for each variable x_i



Output Node: linear combination of hidden nodes

$$f(\vec{x}) = \Sigma\, w'_k\, n_k(\vec{x},\vec{w}_k)$$



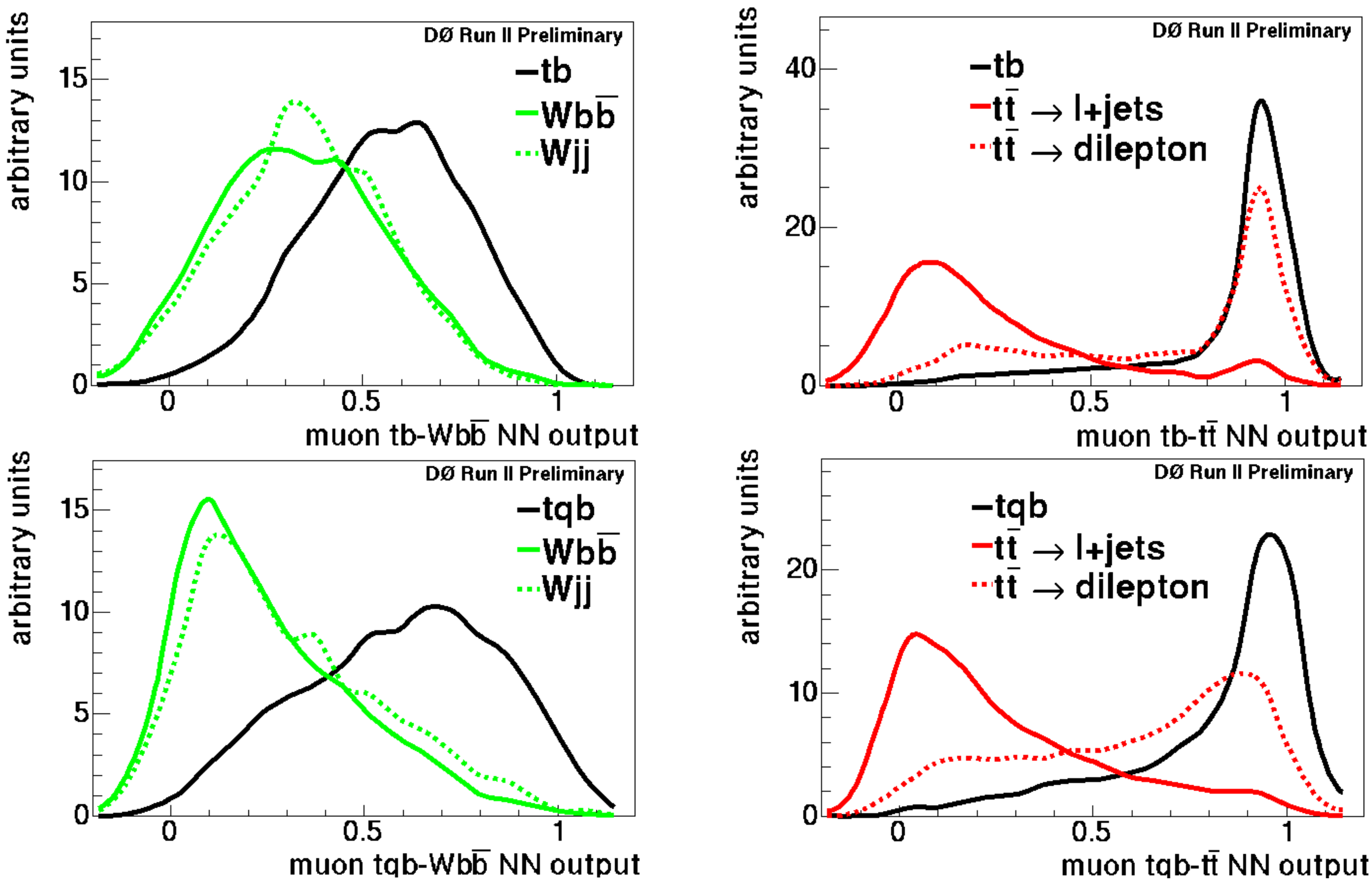


Hidden Nodes: Each is a sigmoid dependent on the input variables

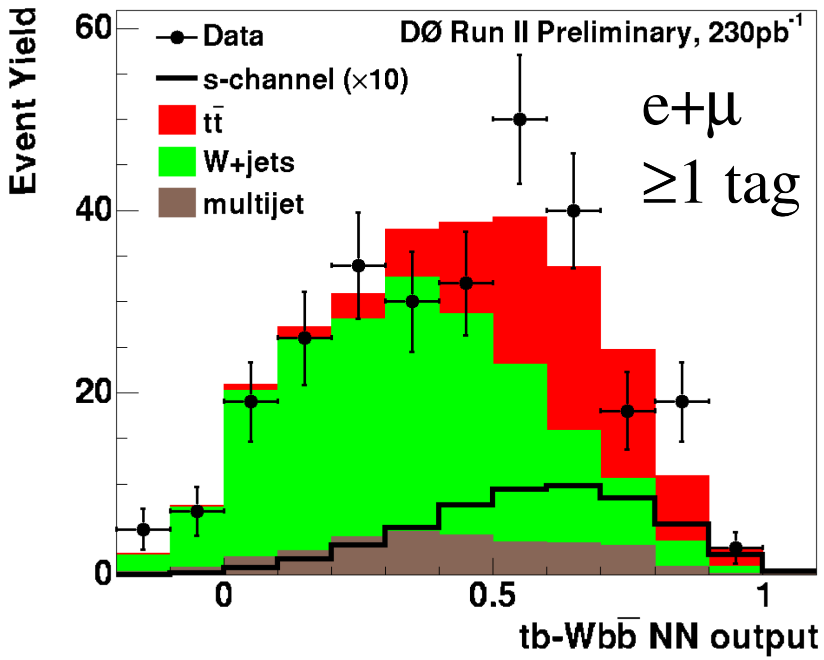
$$n_k(\vec{x},\vec{w}_k) = \frac{1}{1 + e^{-\Sigma\, w_{ik}\, x_i}}$$

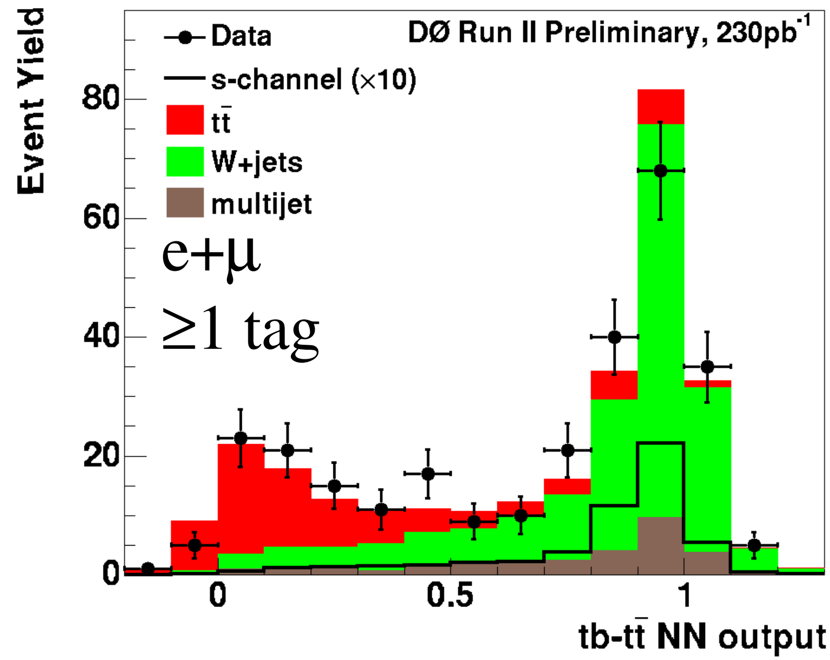
Neural Network Filters

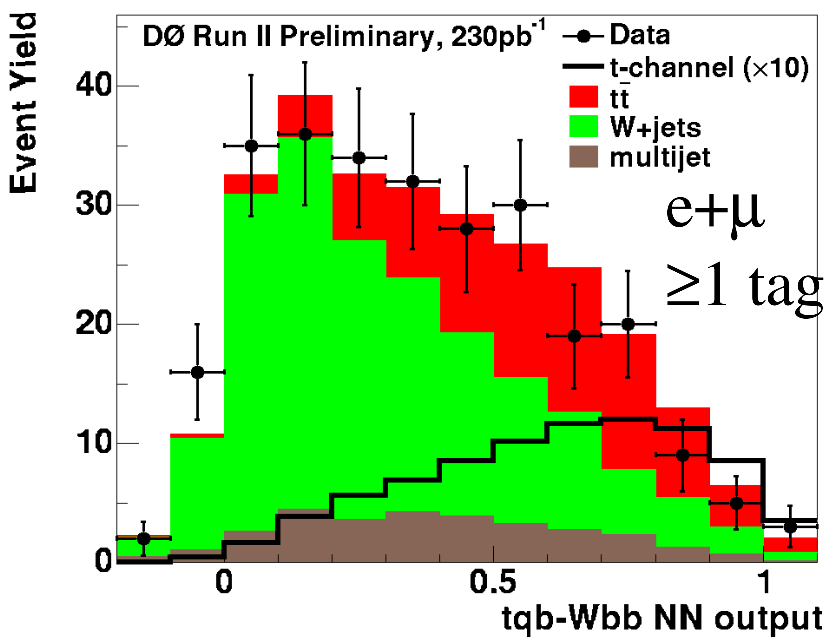
- Focus on the largest backgrounds: Wbb and $t\bar{t} \rightarrow l$+jets
- Same variables for electron and muon channel
- Same filter for =1 tag and ≥2 tags

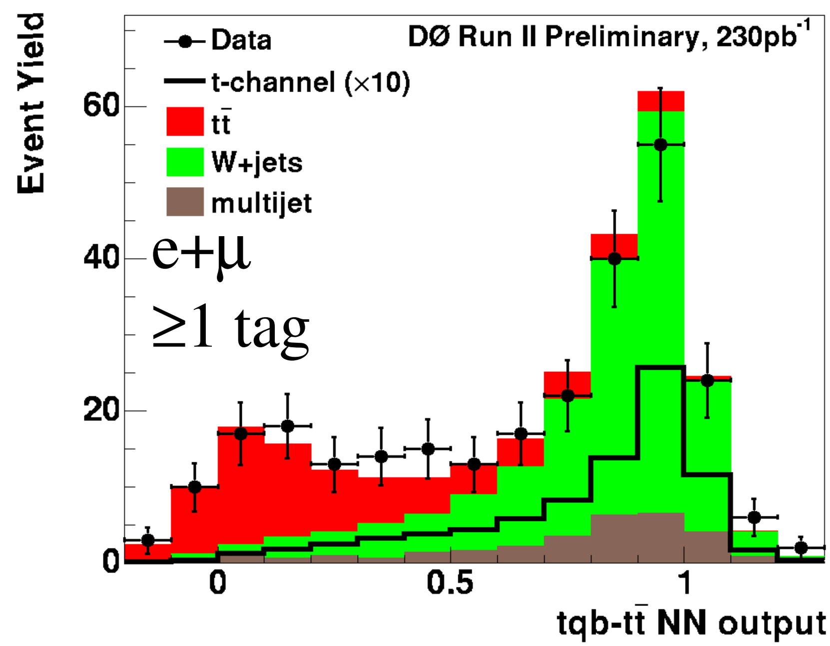


Neural Network Output





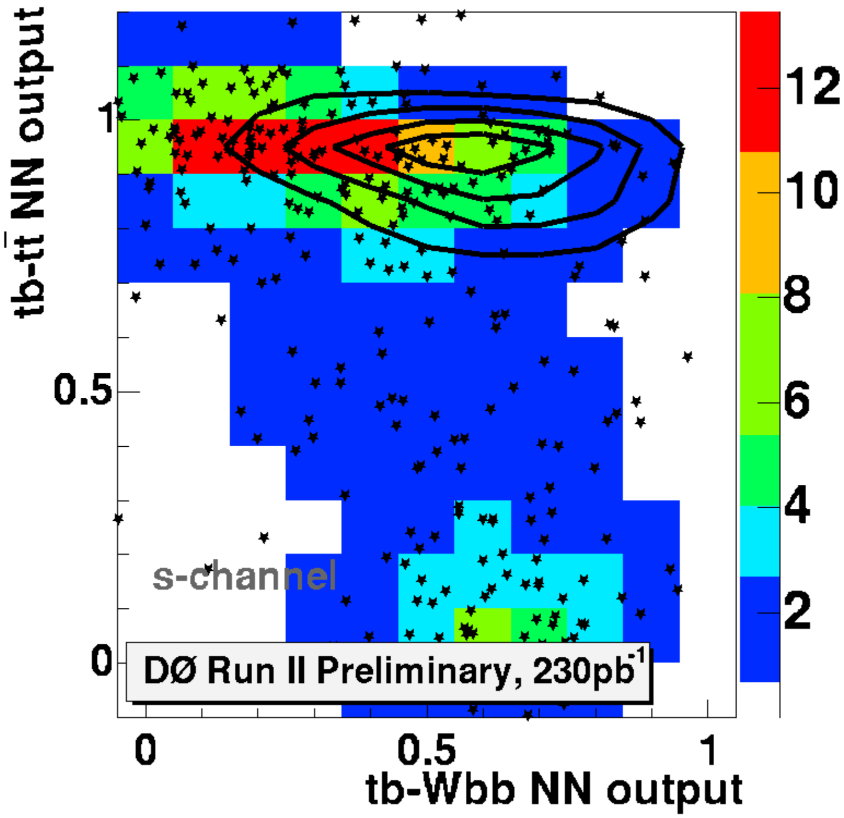


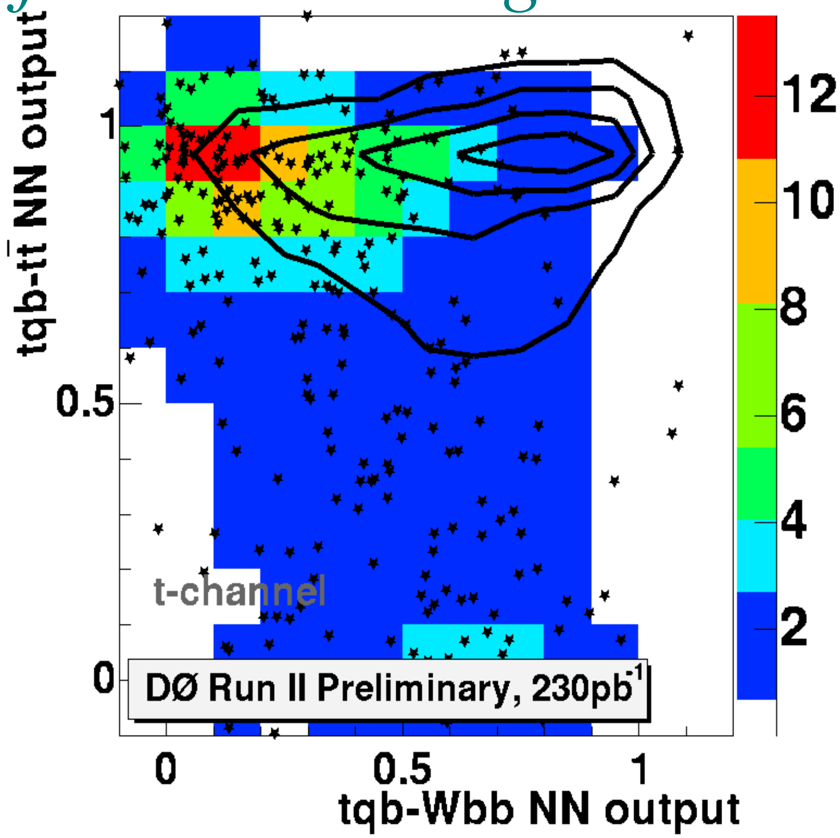


Result

- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limit
  - – Using Bayesian approach and binned likelihood
  - – Including bin-by-bin systematics and correlations

Build binned likelihood from 2-d histograms



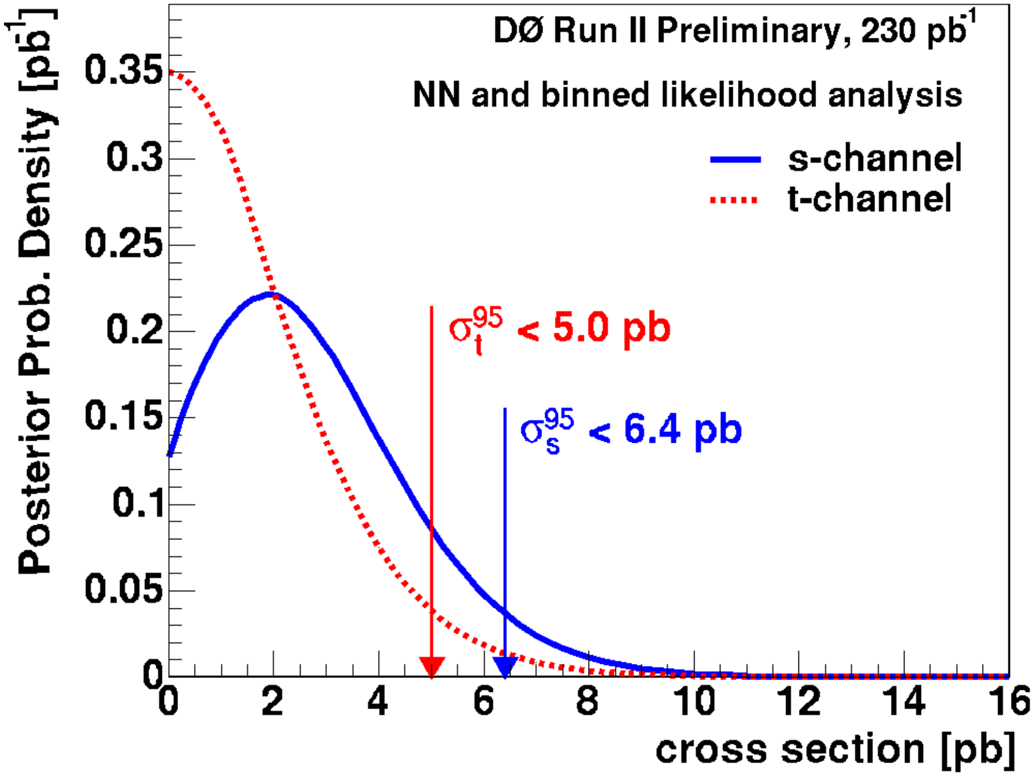


Result

Expected/Observed limit:

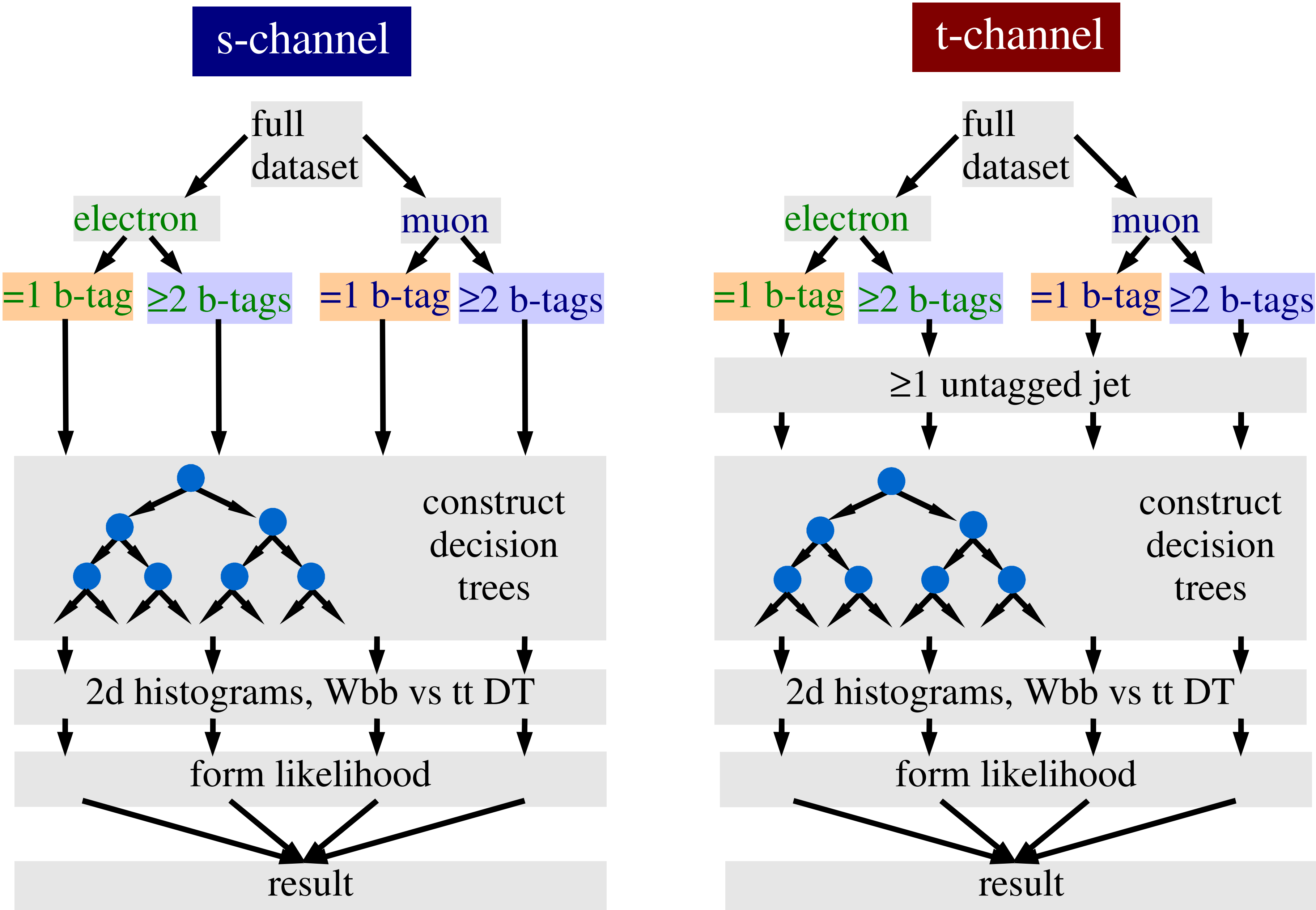
$\sigma_s < 4.5 / 6.4$ pb

$\sigma_t < 5.8 / 5.0$ pb



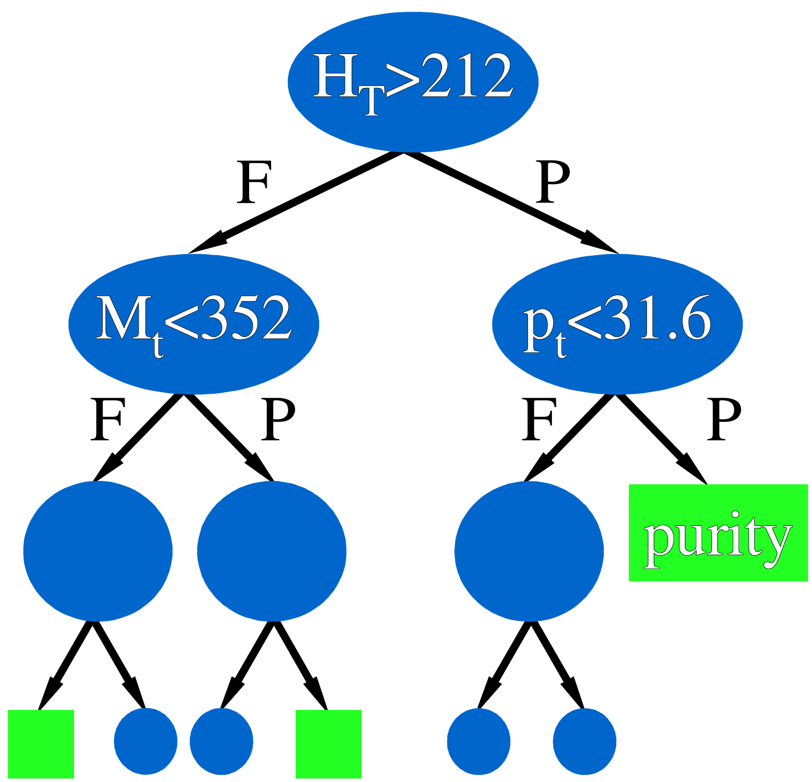
- Most sensitive analysis method
- Improvement compared to cut-based analysis due to:
  - Multivariate analysis
  - Binned likelihood fit

3. Decision Tree Analysis

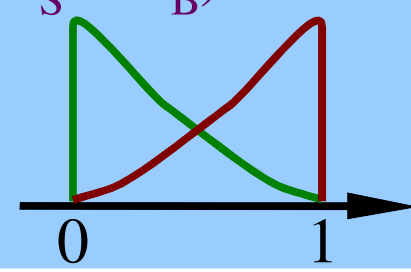


3. Decision Tree Analysis

- For each event, gives probability for an event to be signal
- Widely used in social sciences, recently also in HEP
  - GLAST, Miniboone object ID (see Byron Roe W&C)



- Send each event down the tree
- Each node corresponds to a cut
  - Pass cut (P): right
  - Fail cut (F): left
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$
- Training: optimize Gini improvement
  - Gini = $2\,N_S\,N_B\,/(N_S+N_B)$
- Output: purity for each event



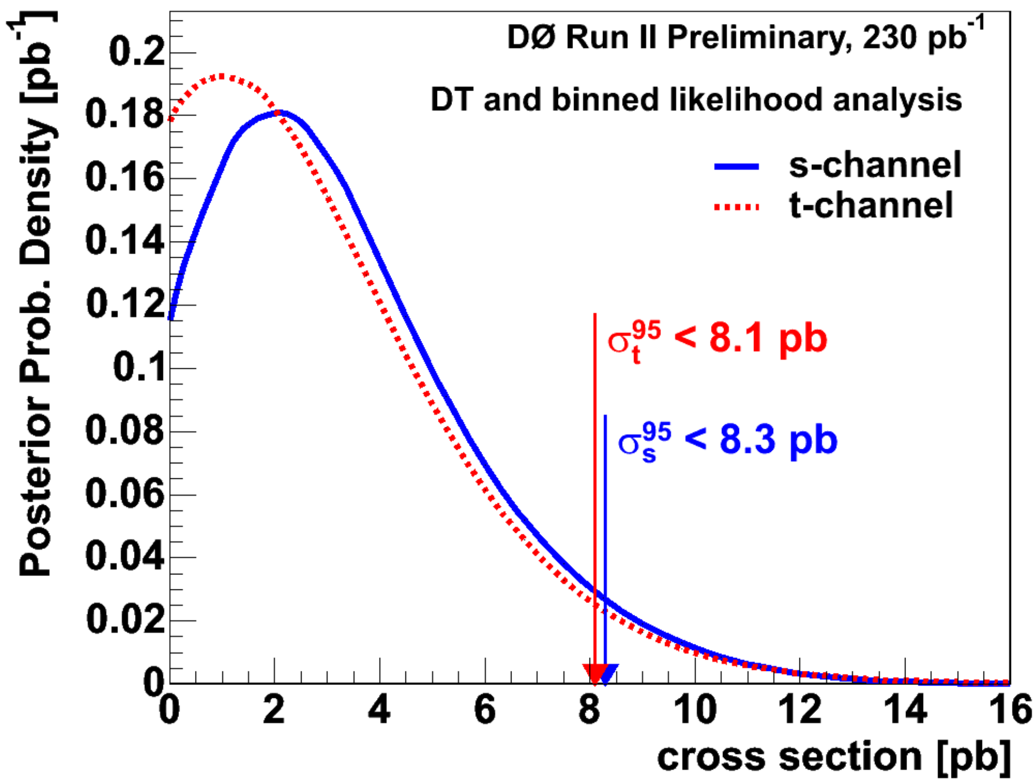
Result

- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limits
  - – Same Bayesian likelihood approach as NN analysis

Expected/Observed limit:

$\sigma_s < 4.5 / 8.3$ pb

$\sigma_t < 6.4 / 8.1$ pb



- Sensitivity comparable to Neural Network analysis

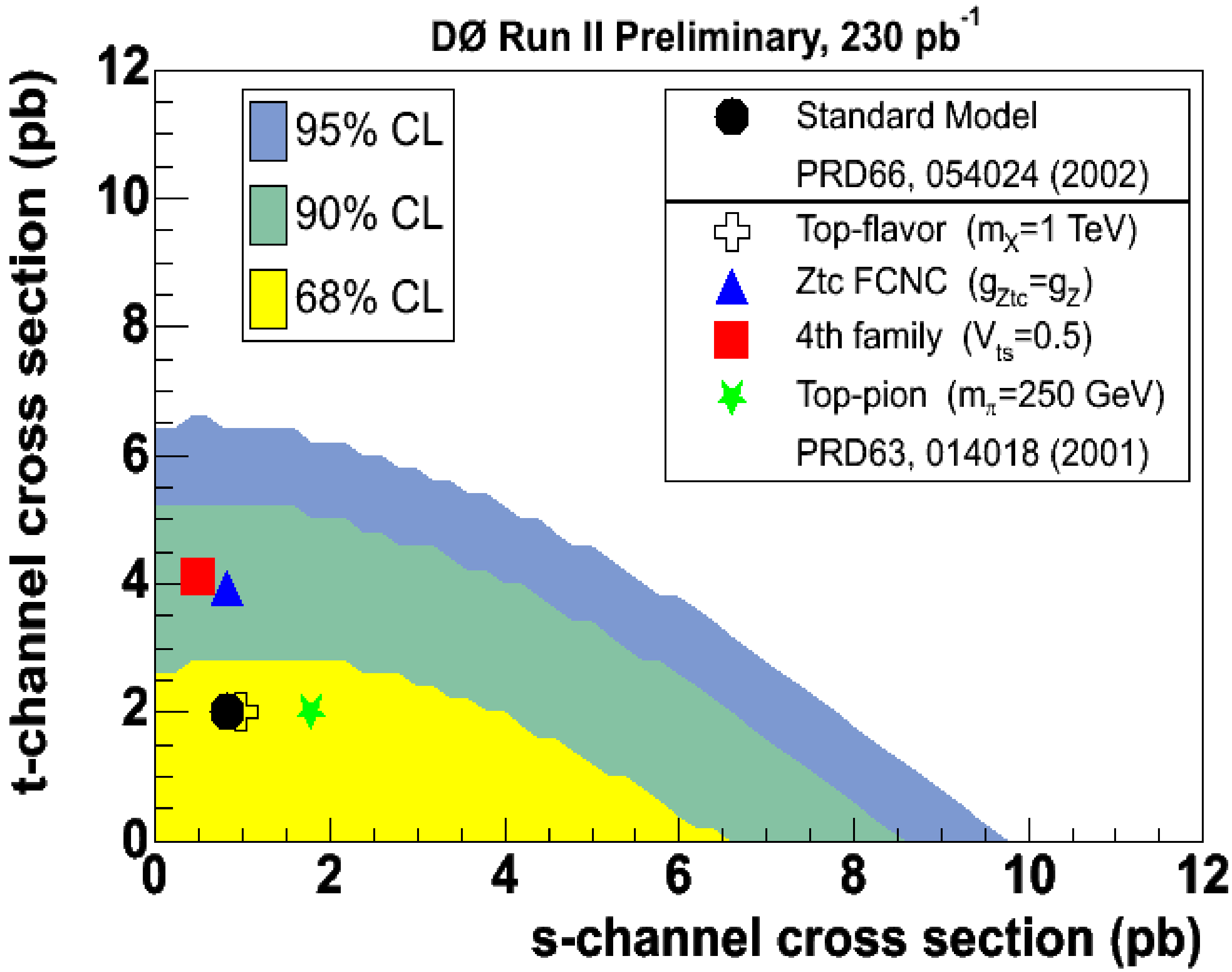
Summary

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb

95% CL upper cross section limits [pb]

DØ Run I	17	22
CDF Run II (160pb^{-1})	13.6	10.1
This analysis (230pb^{-1})		
cut-based	10.6	11.3
DTs & binned likelihood	8.3	8.1
NNs & binned likelihood	6.4	5

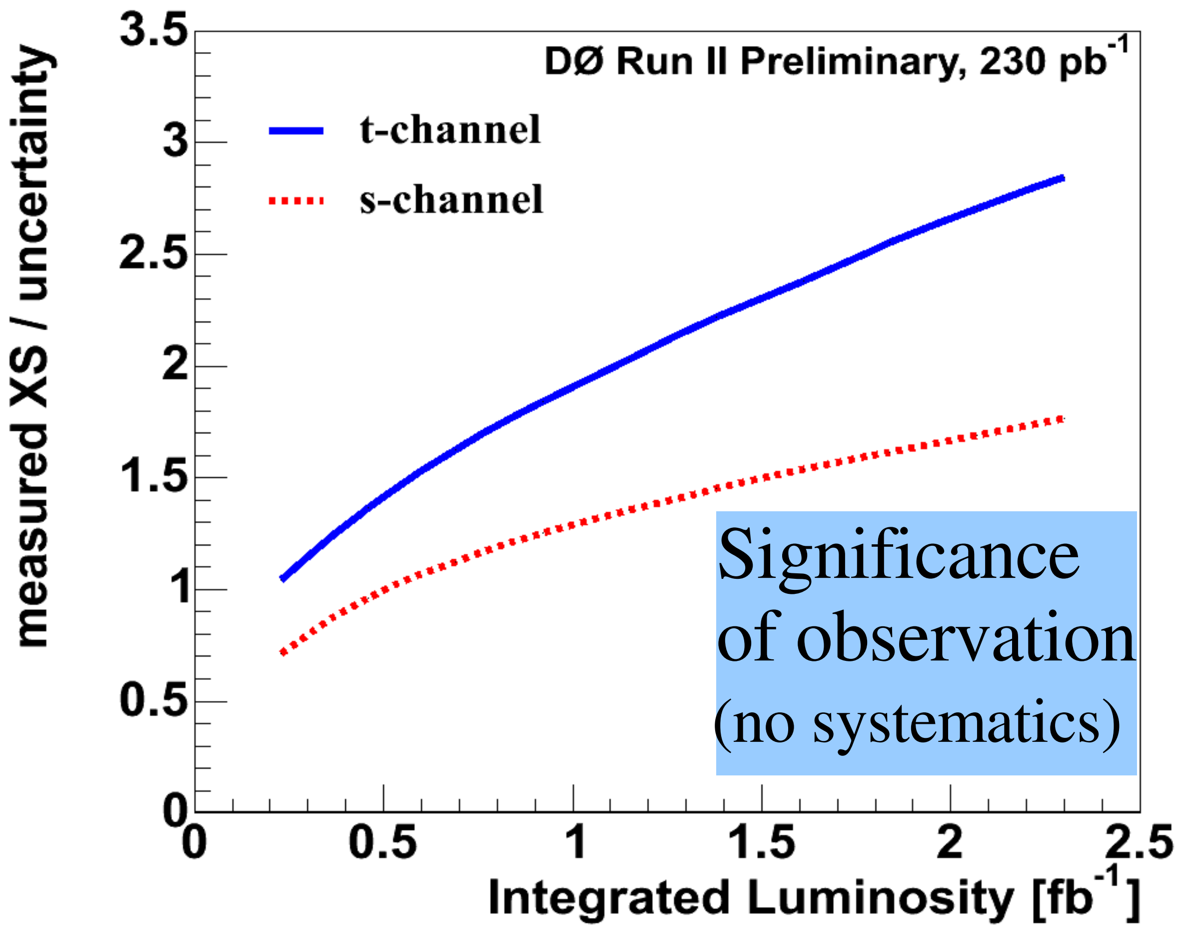
Sensitivity to non-SM Single Top



using only muon channel data

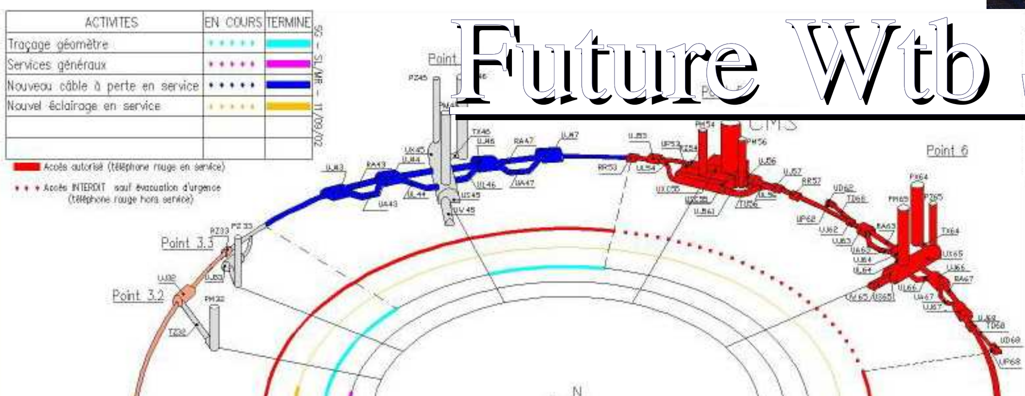
using only electron channel data

Tevatron Single Top Prospects

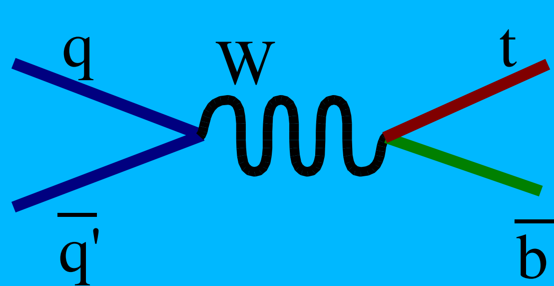


- Observe single top production in Run II
  - Observe new physics (if it's there)
- Measure V_{tb} to ~10%

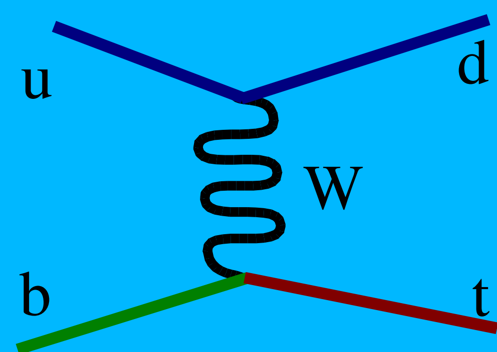
Future Wtb Studies: LHC



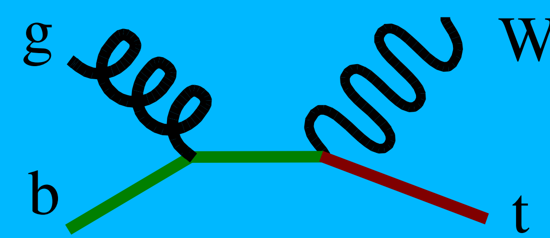

s-channel



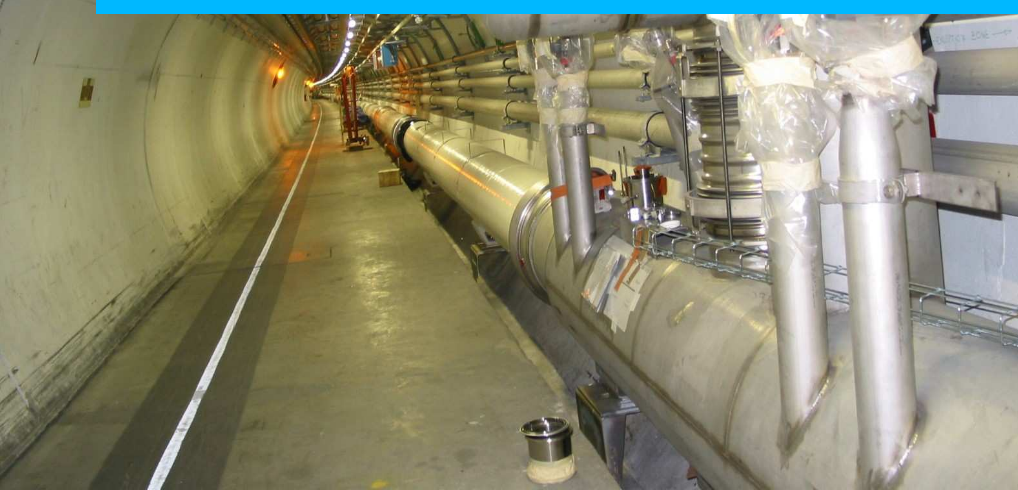
t-channel



associated production



- Observe three single top production modes
- Measure V_{tb} to few %




Conclusions

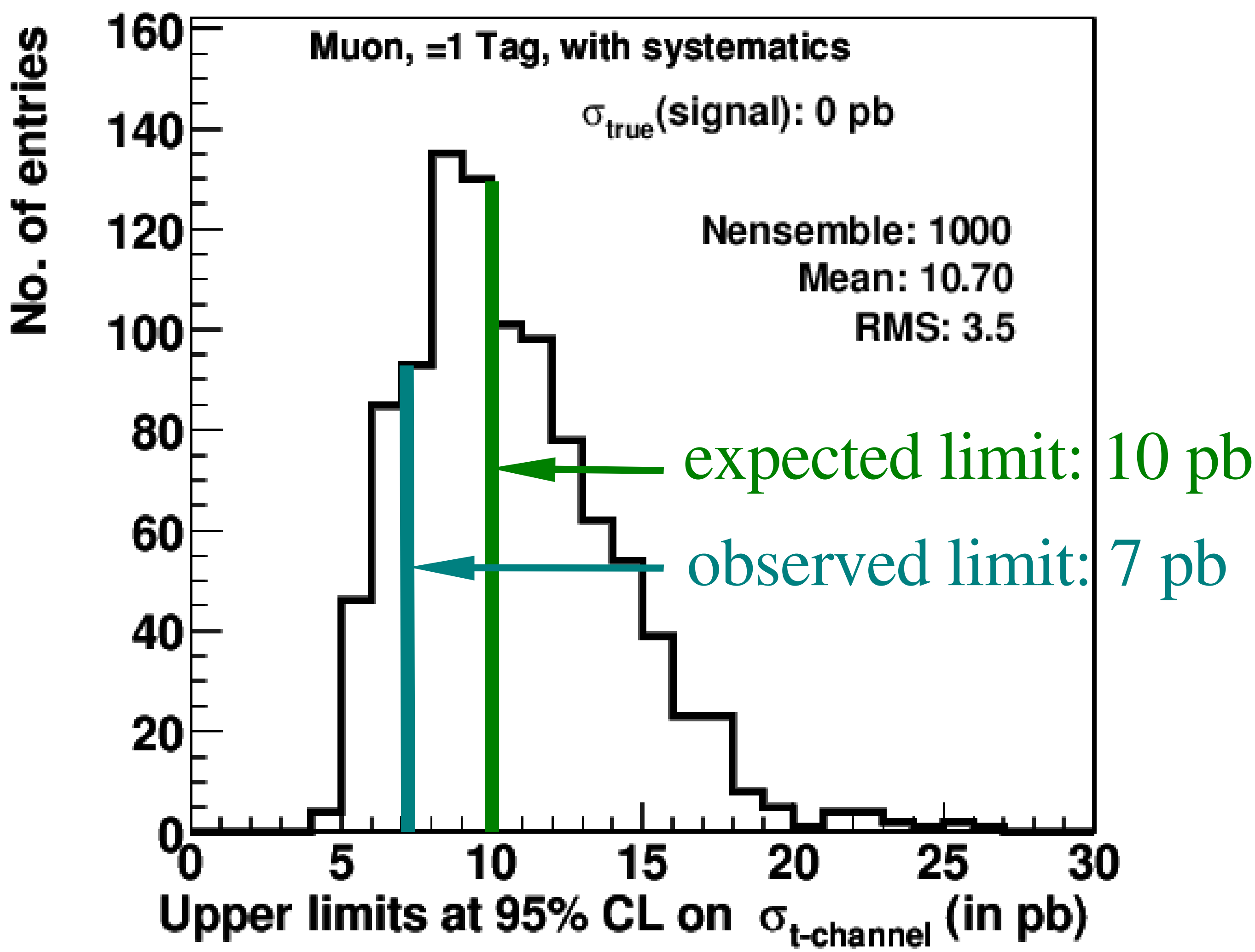
- DØ Run II single top analysis with 230pb^{-1} completed
  - Detector, trigger, software etc working and understood
  - 95% CL cross section limits of $\sigma_s < 6.4$ pb, $\sigma_t < 5.0$ pb
  - Factor 2 improvement over previous limits
  - Reaching sensitivity to new physics
- Single Top is an exciting opportunity for Run II
  - New and old (SM) physics
- This is just the beginning
  - Expect ×3 dataset by end of year
  - Improve all aspects of the analysis

Dawn of Run II Discoveries

Backup Slides

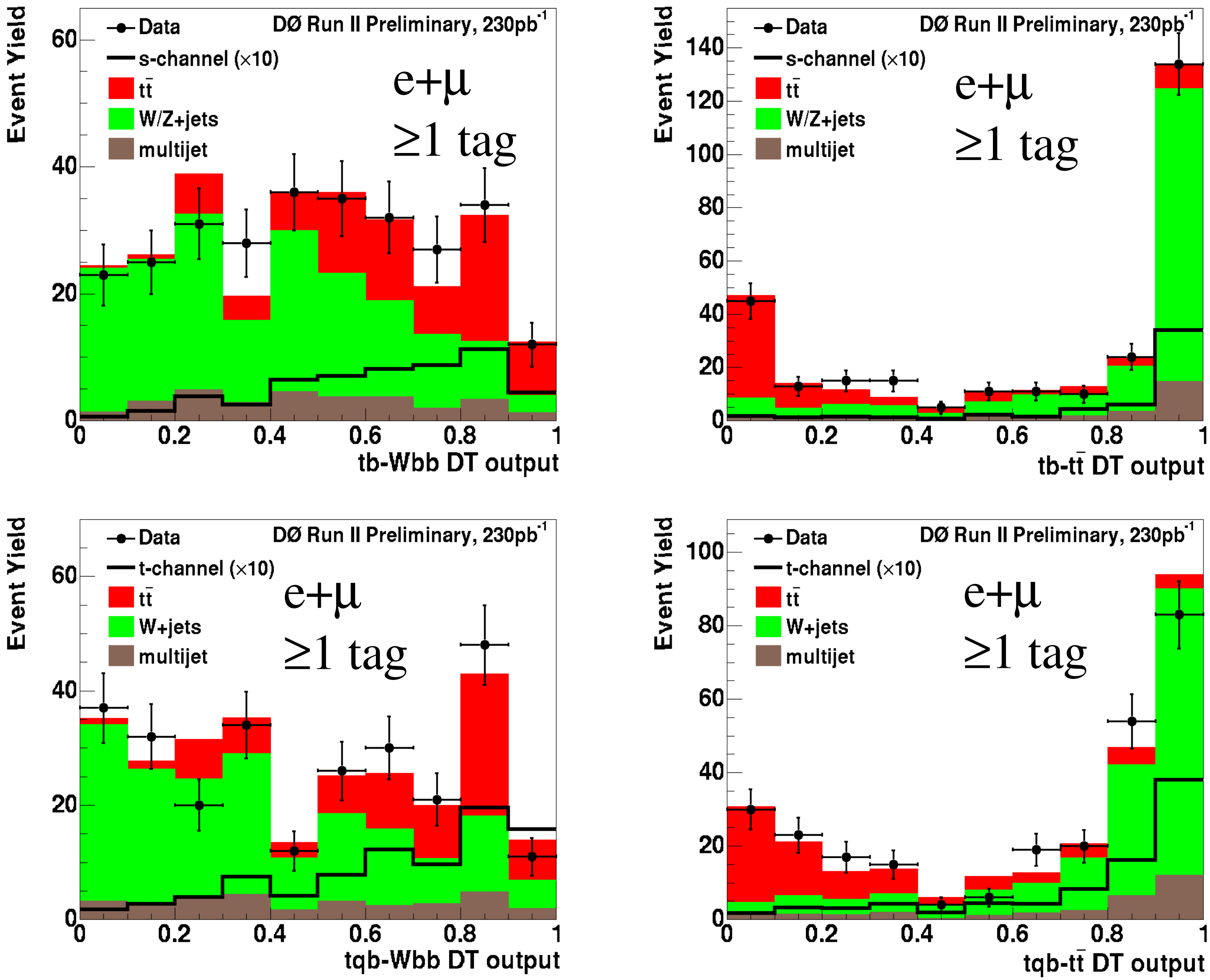
Ensemble Tests

- Limits from pseudo-experiments
  - Vary count in each bin according to Poisson distribution



Decision Tree Output

Follow NN approach closely: Same configuration, samples, variables



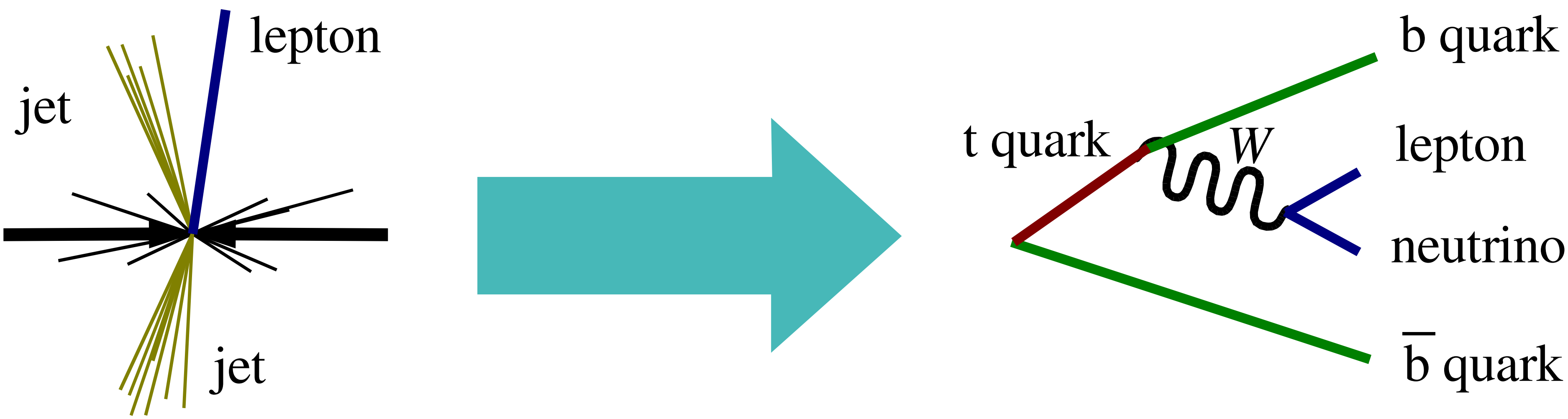
Cut-Based Analysis Details

	s-channel		t-channel	
Channel	Variables	Cuts	Variables	Cuts
Electron				
=1 Tag	$p_T(\mathrm{jet1_{tagged}})$	> 27 GeV	$H_T(\mathrm{alljets})$	> 71 GeV
	$M(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 70 GeV	$M(\mathrm{alljets})$	> 57 GeV
	$\sqrt{\hat{s}}$	> 196 GeV	$\sqrt{\hat{s}}$	> 203 GeV
			$\lvert 175 - M(\mathrm{top_{tagged}})\rvert$	< 57 GeV
			$p_T(\mathrm{jet1_{tagged}})$	> 21 GeV
≥2 Tags	$p_T(\mathrm{jet1_{tagged}})$	> 42 GeV	$p_T(\mathrm{jet1_{tagged}})$	> 34 GeV
	$M(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 98 GeV	$M(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 75 GeV
	$H(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 304 GeV	$H(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 504 GeV
	$H(\mathrm{alljets} - \mathrm{jet_{best}})$	< 304 GeV	$H(\mathrm{alljets} - \mathrm{jet_{best}})$	< 504 GeV
Muon				
=1 Tag	$p_T(\mathrm{jet1_{tagged}})$	> 33 GeV	$\lvert 175 - M(\mathrm{top_{tagged}})\rvert$	< 60 GeV
	$M(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 74 GeV	$\sqrt{\hat{s}}$	> 210 GeV
	$H(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 504 GeV	$M(\mathrm{alljets})$	> 70 GeV
	$H(\mathrm{alljets} - \mathrm{jet_{best}})$	< 504 GeV	$H_T(\mathrm{alljets})$	> 58 GeV
≥2 Tags	$p_T(\mathrm{jet1_{tagged}})$	> 33 GeV	$\lvert 175 - M(\mathrm{top_{tagged}})\rvert$	< 213 GeV
	$M(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 74 GeV		
	$H(\mathrm{alljets} - \mathrm{jet1_{tagged}})$	< 504 GeV		
	$H(\mathrm{alljets} - \mathrm{jet_{best}})$	< 504 GeV		

Variables:

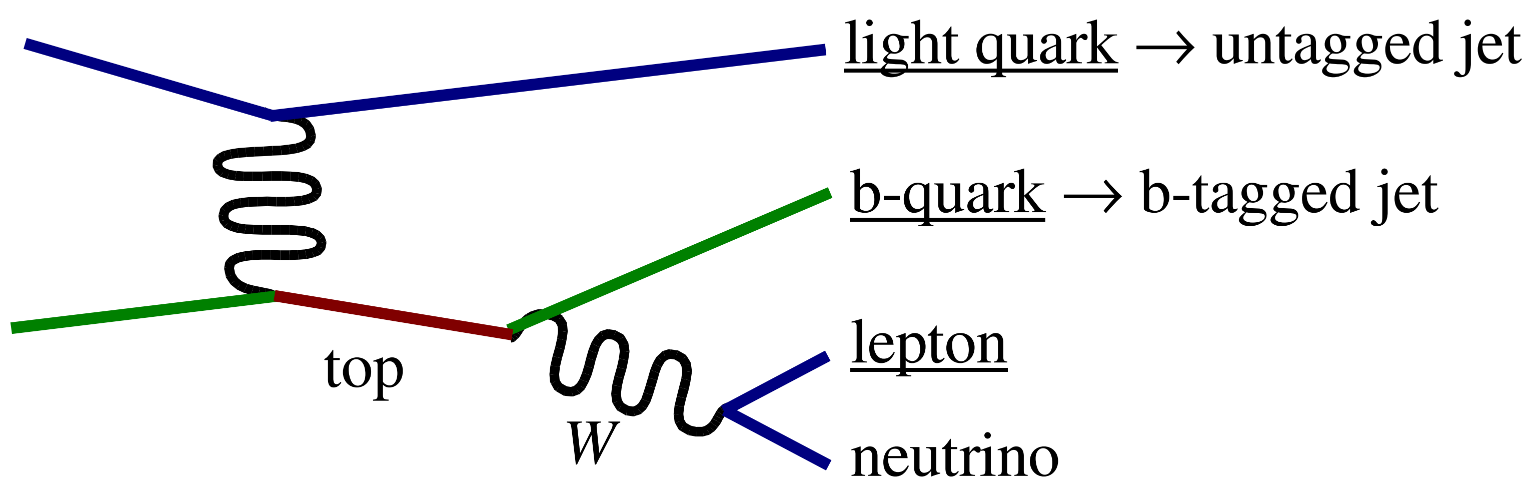
	Signal-Background Pairs			
	tb		tqb	
	Wbb	$t\bar{t}$	Wbb	$t\bar{t}$
Individual object kinematics				
$p_T(\text{jet1}_{\text{tagged}})$	$\surd$	$\surd$	$\surd$	—
$p_T(\text{jet1}_{\text{untagged}})$	—	—	$\surd$	$\surd$
$p_T(\text{jet2}_{\text{untagged}})$	—	—	—	$\surd$
$p_T(\text{jet1}_{\text{nonbest}})$	$\surd$	$\surd$	—	—
$p_T(\text{jet2}_{\text{nonbest}})$	$\surd$	$\surd$	—	—
Global event kinematics				
$M_T(\text{jet1,jet2})$	$\surd$	—	—	—
$p_T(\text{jet1,jet2})$	$\surd$	—	$\surd$	—
$M(\text{alljets})$	$\surd$	$\surd$	$\surd$	$\surd$
$H_T(\text{alljets})$	—	—	$\surd$	—
$M(\text{alljets} - \text{jet1}_{\text{tagged}})$	—	—	—	$\surd$
$H(\text{alljets} - \text{jet1}_{\text{tagged}})$	—	$\surd$	—	$\surd$
$H_T(\text{alljets} - \text{jet1}_{\text{tagged}})$	—	—	—	$\surd$
$p_T(\text{alljets} - \text{jet1}_{\text{tagged}})$	—	$\surd$	—	$\surd$
$M(\text{alljets} - \text{jet}_{\text{best}})$	—	$\surd$	—	—
$H(\text{alljets} - \text{jet}_{\text{best}})$	—	$\surd$	—	—
$H_T(\text{alljets} - \text{jet}_{\text{best}})$	—	$\surd$	—	—
$M(\text{top}_{\text{tagged}}) = M(W,\text{jet1}_{\text{tagged}})$	$\surd$	$\surd$	$\surd$	$\surd$
$M(\text{top}_{\text{best}}) = M(W,\text{jet}_{\text{best}})$	$\surd$	—	—	—
$\sqrt{\hat{s}}$	$\surd$	—	$\surd$	$\surd$
Angular variables				
$\Delta R(\text{jet1,jet2})$	$\surd$	—	$\surd$	—
$Q(\text{lepton}) \times \eta(\text{jet1}_{\text{untagged}})$	—	—	$\surd$	$\surd$
$\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$	$\surd$	—	—	—
$\cos(\text{lepton}, \text{jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$	—	—	$\surd$	—
$\cos(\text{alljets}, \text{jet1}_{\text{tagged}})_{\text{alljets}}$	—	—	$\surd$	$\surd$
$\cos(\text{alljets}, \text{jet}_{\text{nonbest}})_{\text{all jets}}$	—	$\surd$	—	—

Maximize Sensitivity:
Final State Reconstruction



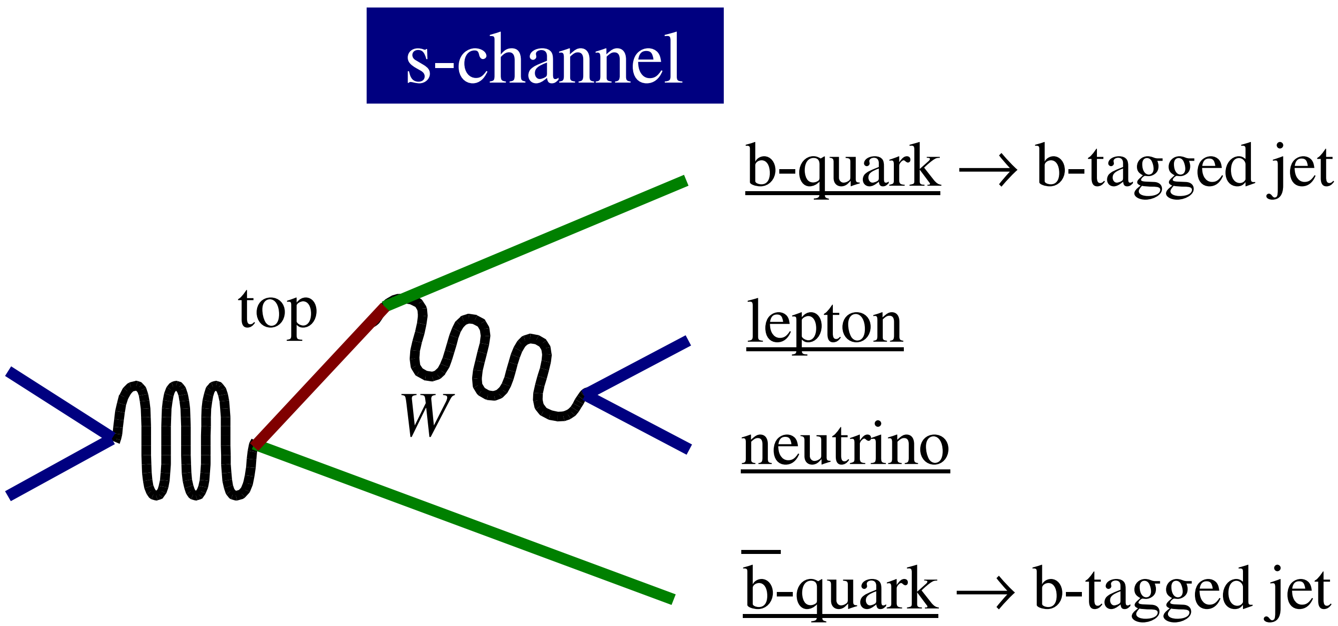
Final State Reconstruction

t-channel



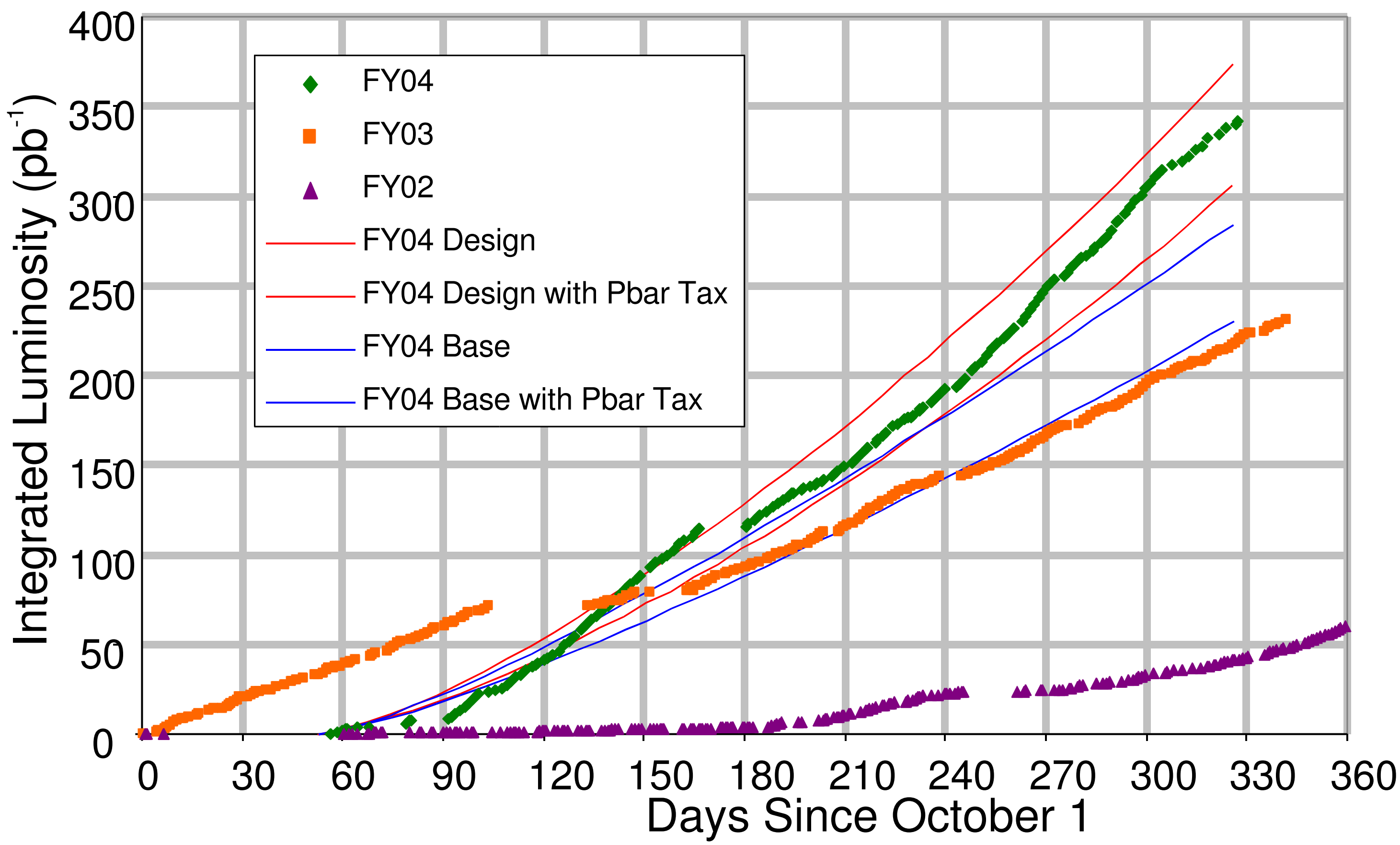
- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and leading b-tagged jet
- Reconstruct light quark as leading untagged jet

Final State Reconstruction



- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and one of the jets using Best Jet Algorithm:
  - Pick jet for which $M(W,\text{jet})$ is closest to true top mass (175GeV)
- Reconstruct $\bar{b}$-quark as leading non-best jet

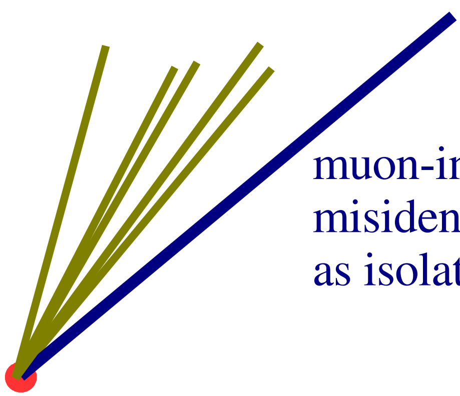
Tevatron Integrated Luminosity per year



- Tevatron delivered luminosity is exceeding "baseline" and "design" projections

Mis-reconstructed Events?

- Cosmic rays (muons)
- Mis-reconstructed vertex
  - Affects missing transverse energy
- Mis-reconstructed jets
  - fake electron
  - fake isolated muon

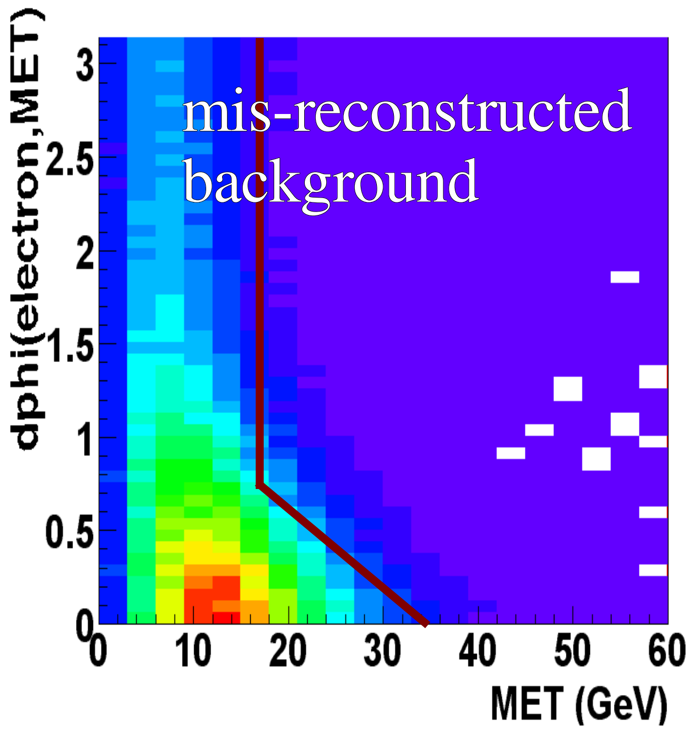


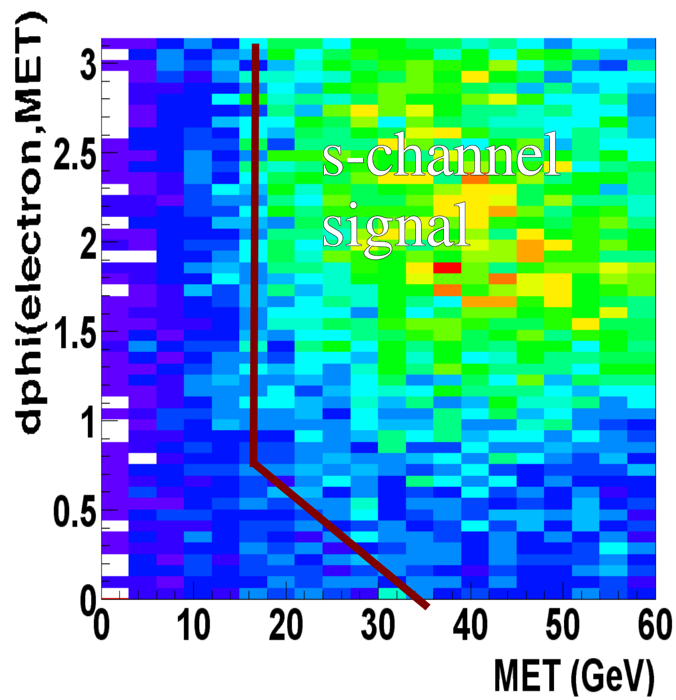
muon-in-jet misidentified as isolated

→ Primary vertex constraints

- Primary vertex with ≥3 tracks
- Lepton is required to originate from primary vertex

→ Triangle Cuts



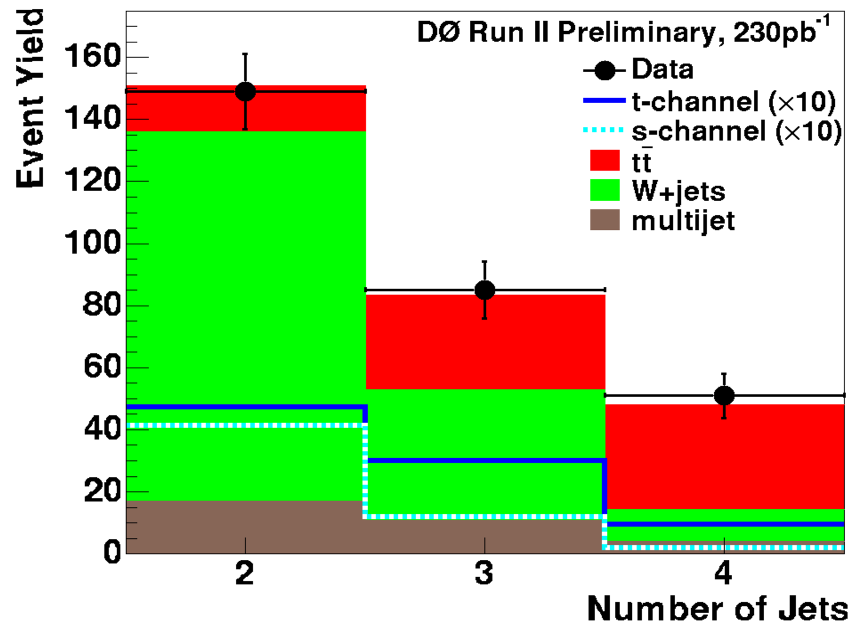


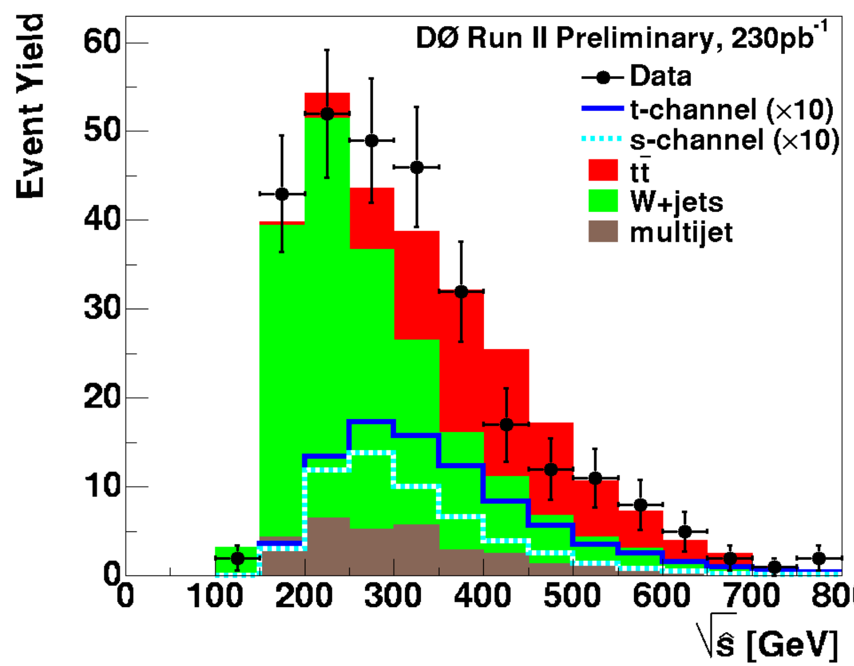
Event Yield

$$Y = L \times \sigma \times Br \times Acc(cuts) \times Eff(b\text{-}tag)$$

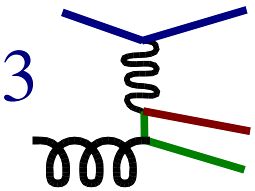
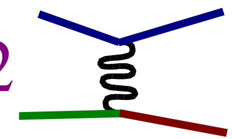
	Acc(cuts)	Eff(b-tag)
s-channel:	23%	54%
t-channel:	22%	38%

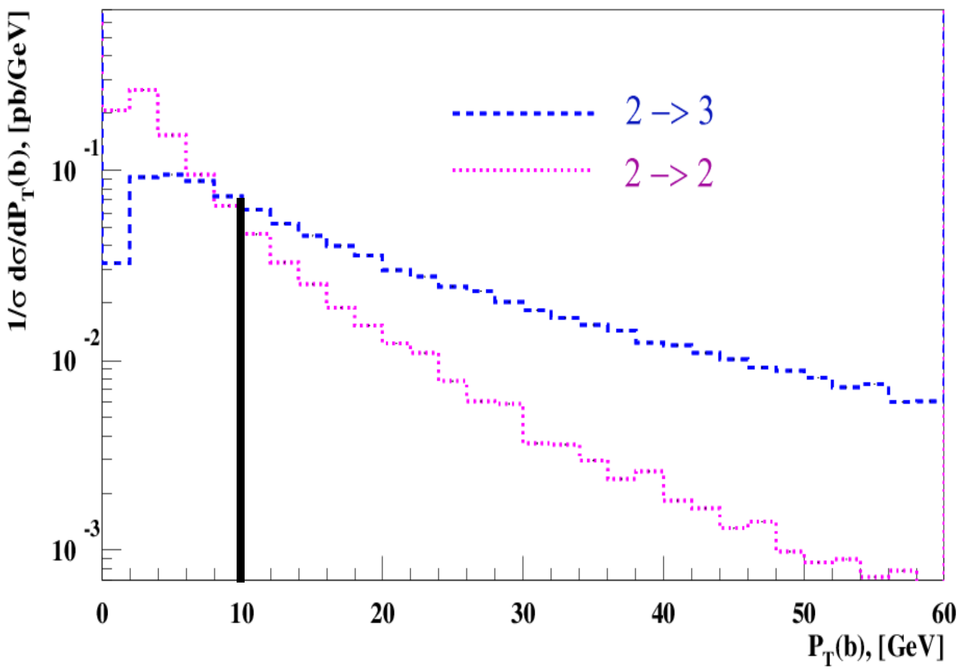
	Event Yields	
	s-channel search	t-channel search
s-channel signal	5.5	4.7
t-channel signal	8.6	8.5
W+jets	169	164
top pairs	78	76
multijet	31	31
Background sum	287±44	276±41
Observed	283	271

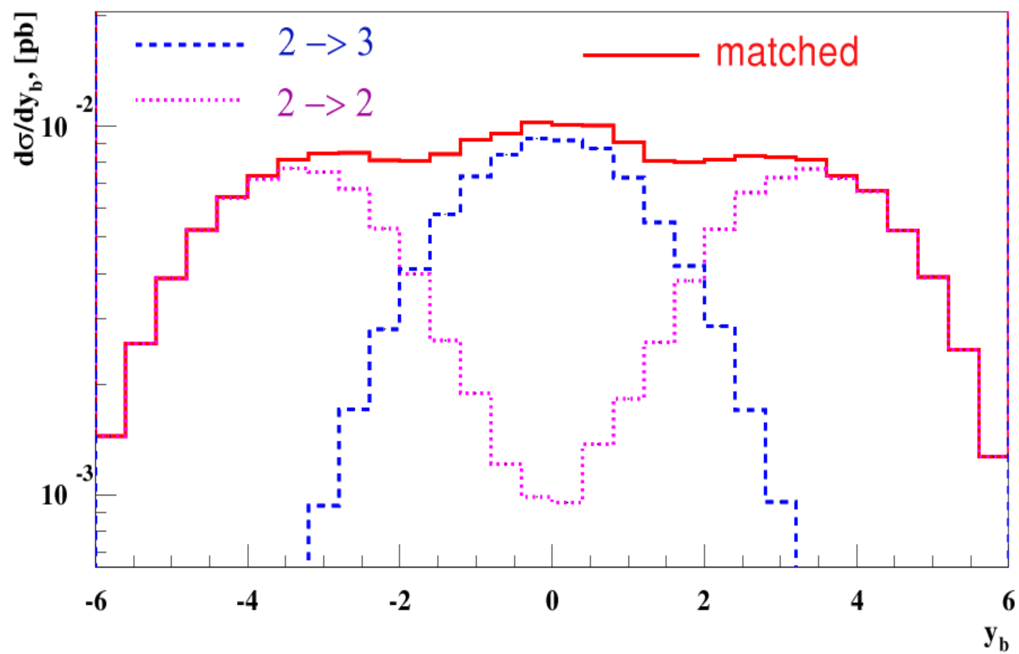




Signal Modeling

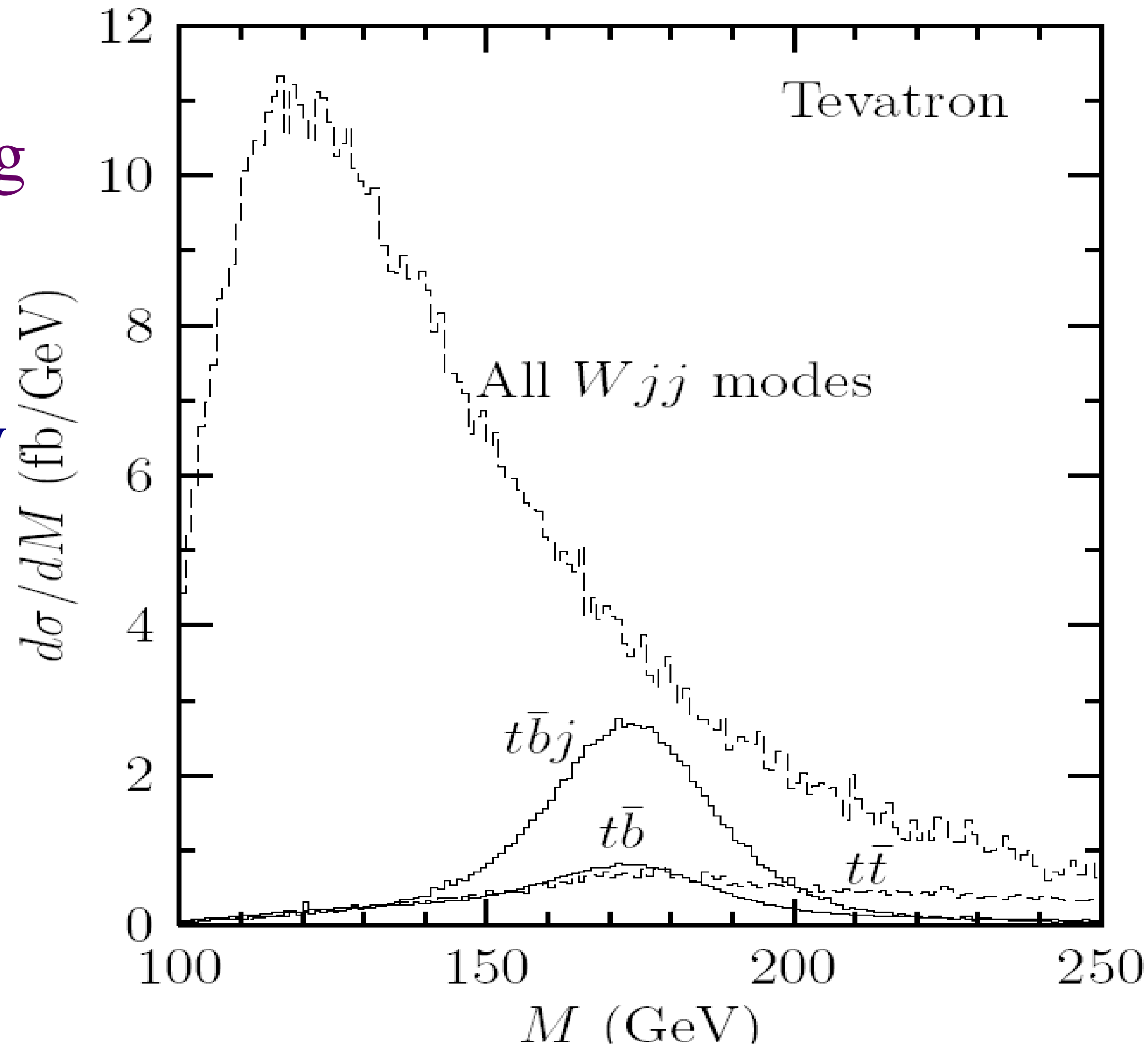
- CompHEP-based generator
  - Includes $O(\alpha_s)$ diagrams → reproduces NLO distributions
  - Including top quark spin correlations
- Normalize to NLO cross sections
- t-channel: match 2→3  and 2→2  processes





Single Top – Expectation

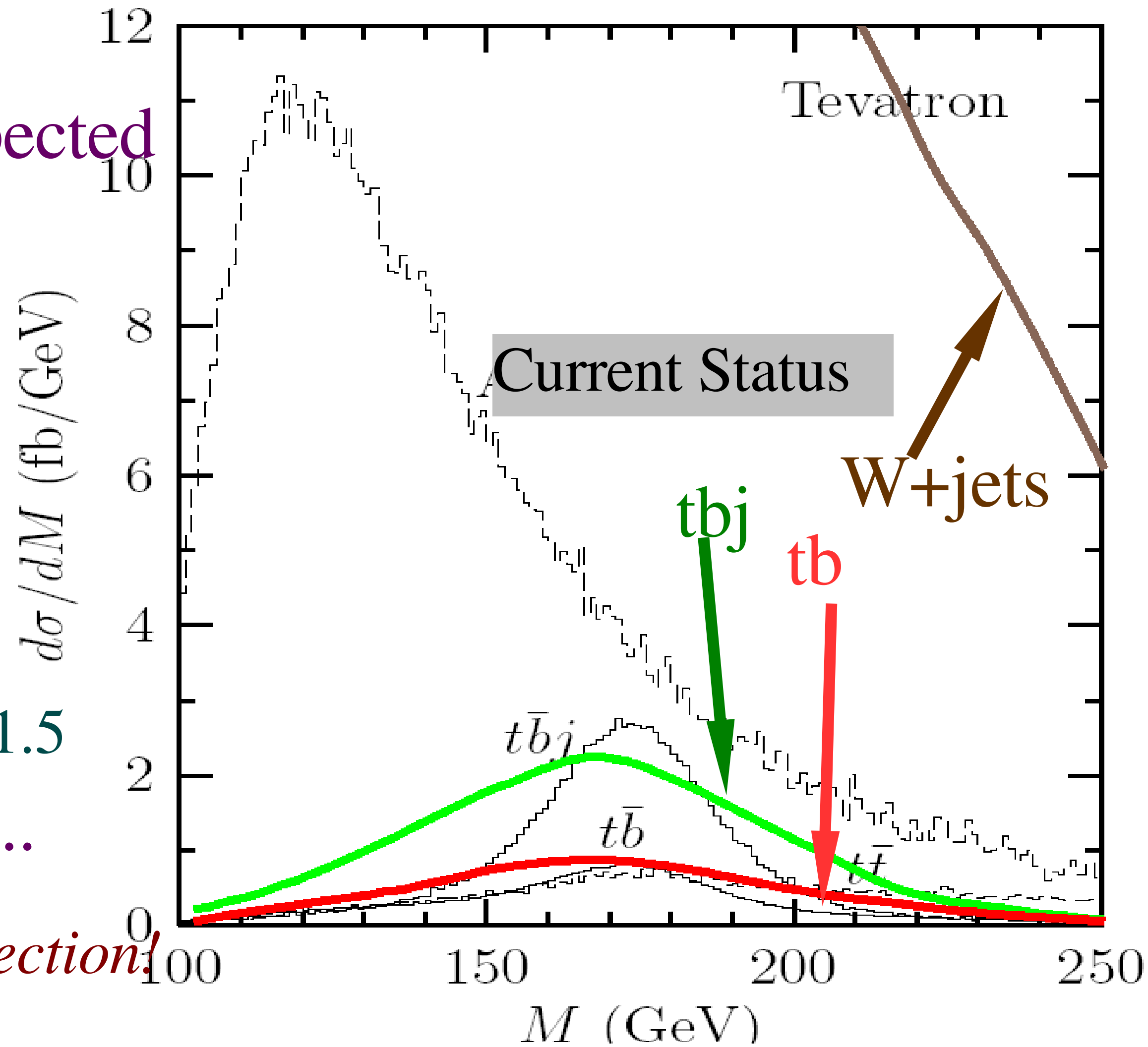
- Predictions for Run II were to be sensitive to single top production with ~500pb^{-1} – *Where is it?*
  - Observation with 2fb^{-1}
  - Starting to be interesting much sooner
- We have recorded >400pb at DØ already
  - Observation soon?



Stelzer, Sullivan, Willenbrock, PRD58 (98)

Single Top – Expectation vs Reality

- Predictions for Run II were to be sensitive to single top production with ~500pb^{-1} – *Where is it?*
  - Detector performance not (yet) as good as expected
    - b-tagging ~45% per jet
    - Trigger, ID <100%
    - Jet resolution not (yet) as good as expected
  - W+jets background larger than expected
    - NLO calculations: LO×1.5
  - Top mass, gluon PDF, …

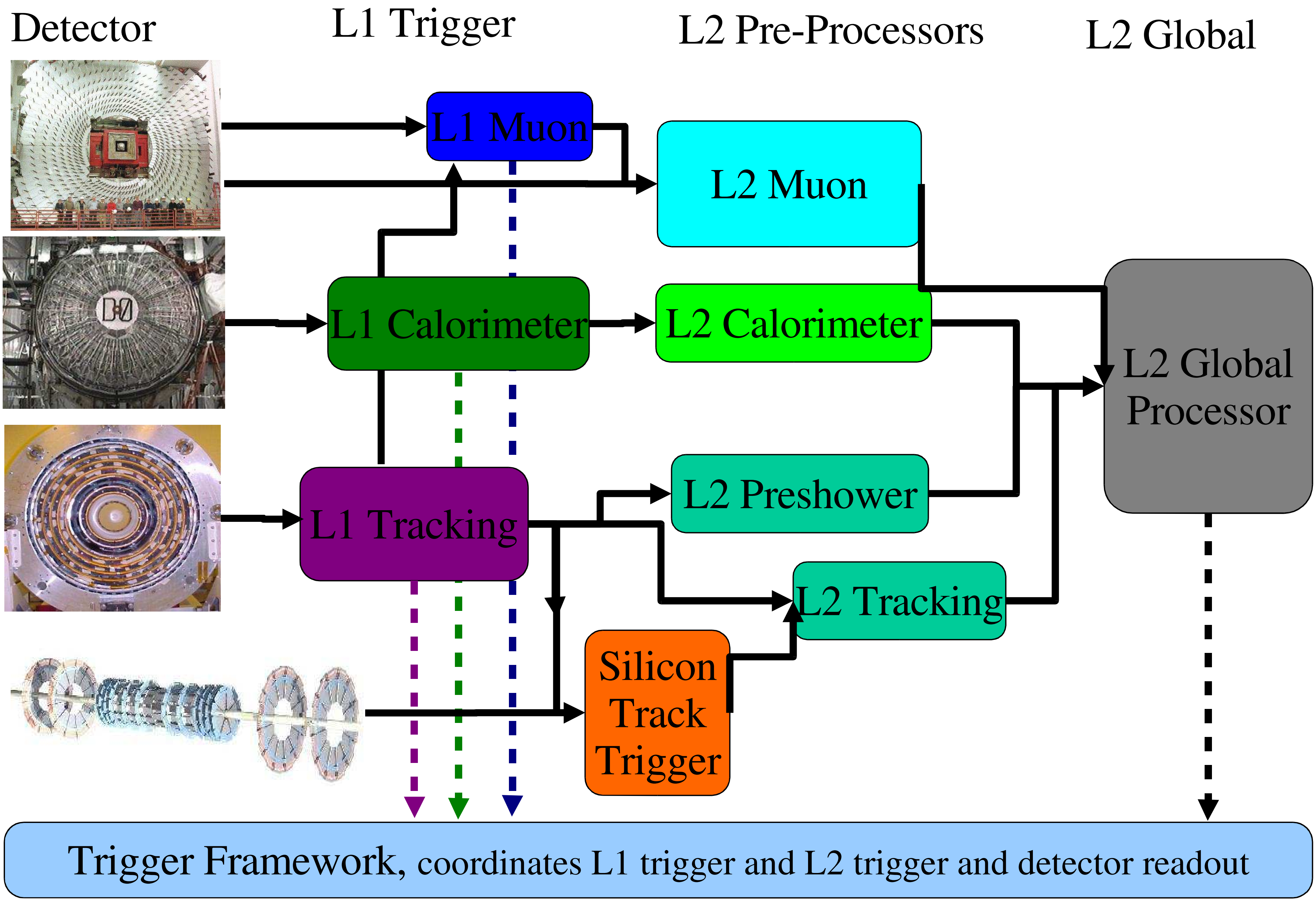


Many effects, all in the wrong direction!

Level 2 Trigger

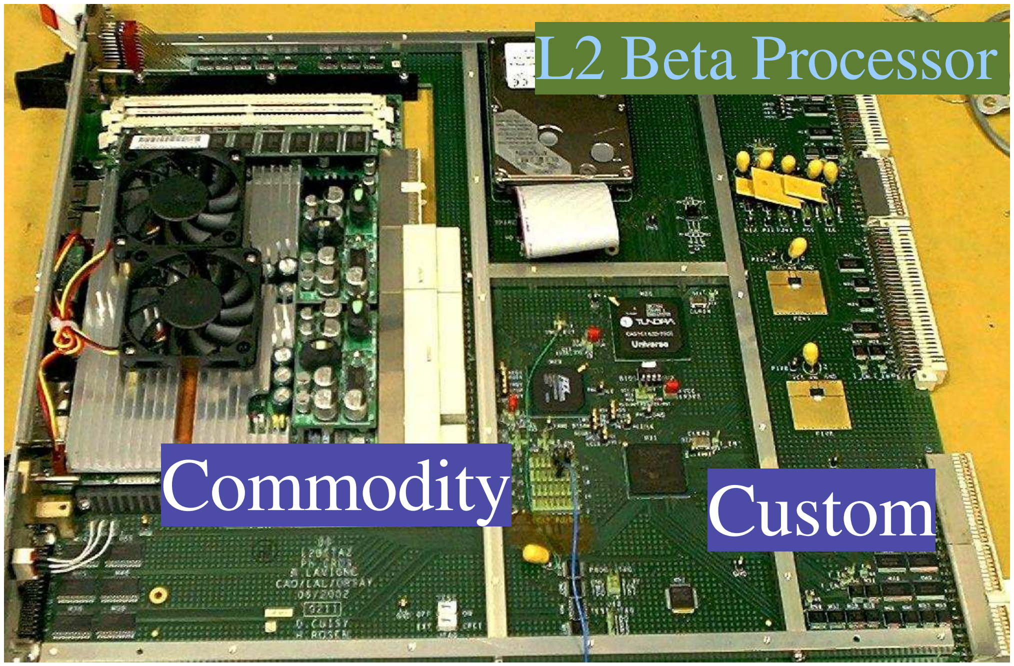
- Design: reduce 6kHz L1 accept rate to 1kHz
- Both custom hardware/firmware and commodity-based components
  - Dataflow from L1 and detector systems in custom systems
  - Algorithms in software running on commodity-based system
- Build Physics objects
  - Jets and EM objects are built from L1 calorimeter towers
  - Central tracks are built from L1 track trigger tracks
    - Now also Secondary Vertex Tagging
  - Muons are reconstructed from raw muon chamber hits
- Combine objects from different detector systems
  - Track matching to muons, electrons, or jets
- Allow for 128 different combinations
  - 1-1 matching of bits between L1 and L2

Trigger Level 1/Level 2 Dataflow



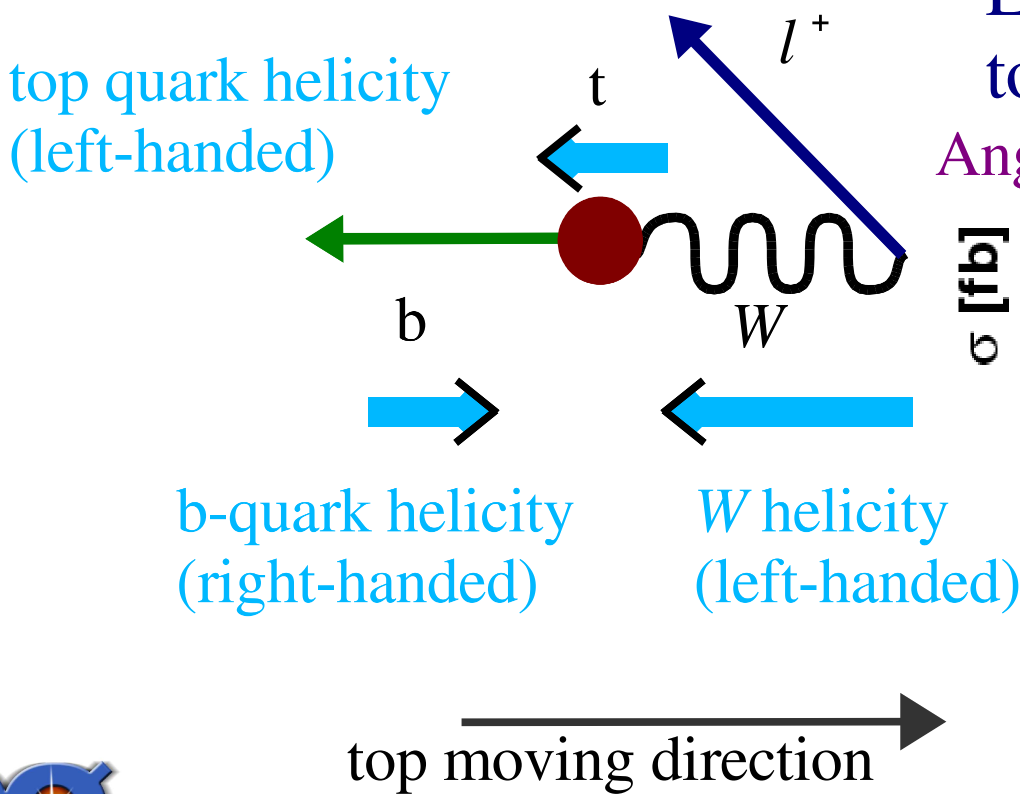
Trigger Hardware: Custom-built vs Commodity

- Trigger Level 1/Level 2 relies heavily on custom-built hardware/firmware
  - Cards designed/built mostly by Engineers – feedback from Physicists
  - Systems commissioned mostly by Physicists – help from Engineers
  - Firmware written by Engineers/Physicists
    - Most Firmware tasks too complex to be written by Physicists alone
- Trigger Level 2/Level 3 relies heavily on commodity systems
  - Off-the-shelf products (computers, interfaces/cables)
  - Interfaced to custom-built cards
  - Software written by Physicists



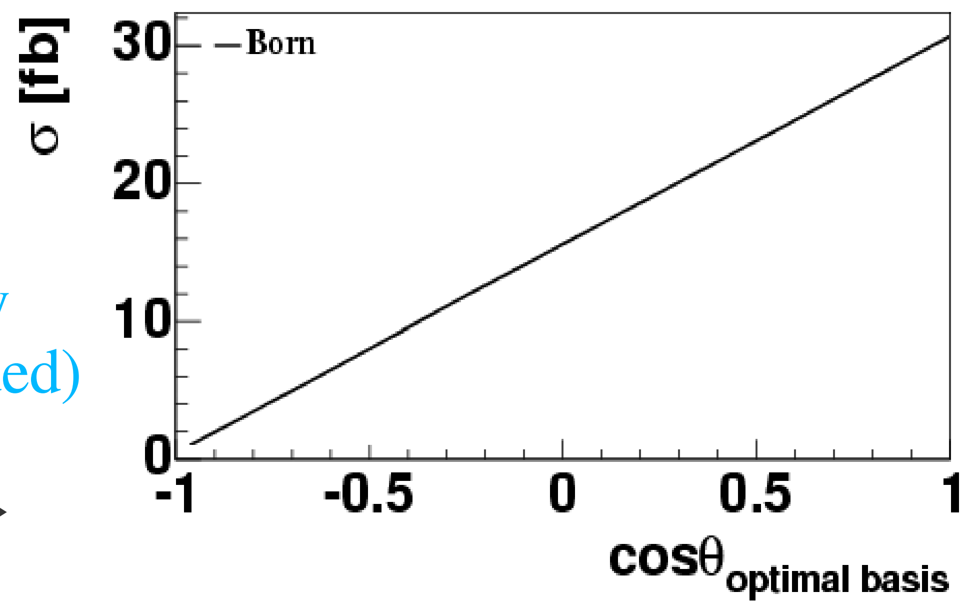
Top Quark Spin

- Top Quark decays before it hadronizes
  - Full spin information is preserved in the decay products
  - Electroweak charged current interaction is left-handed
- Top polarization in the top rest frame:



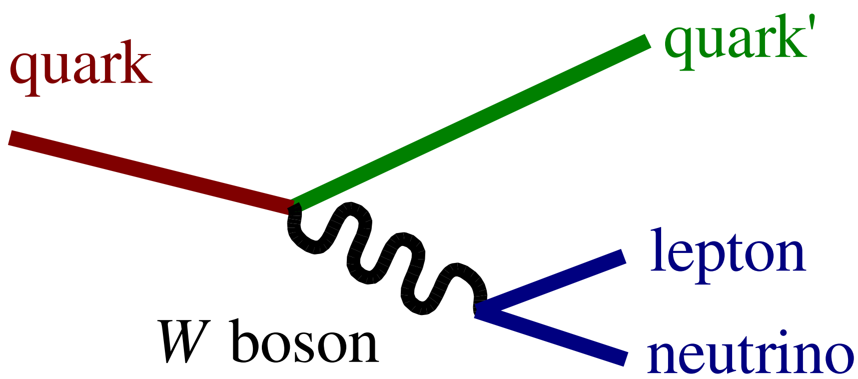
Lepton moves along top spin direction

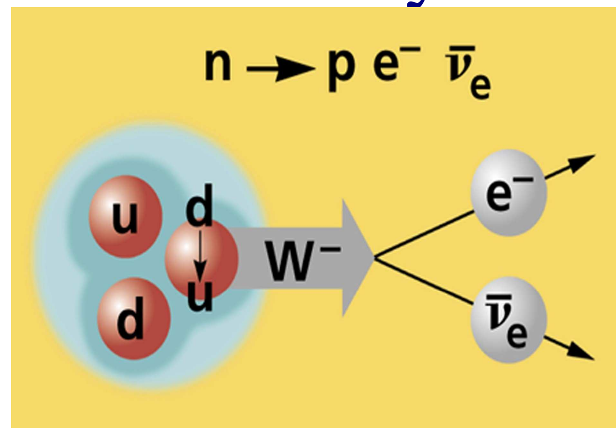
Angle between light quark and lepton:



Quark Charged Current Interactions

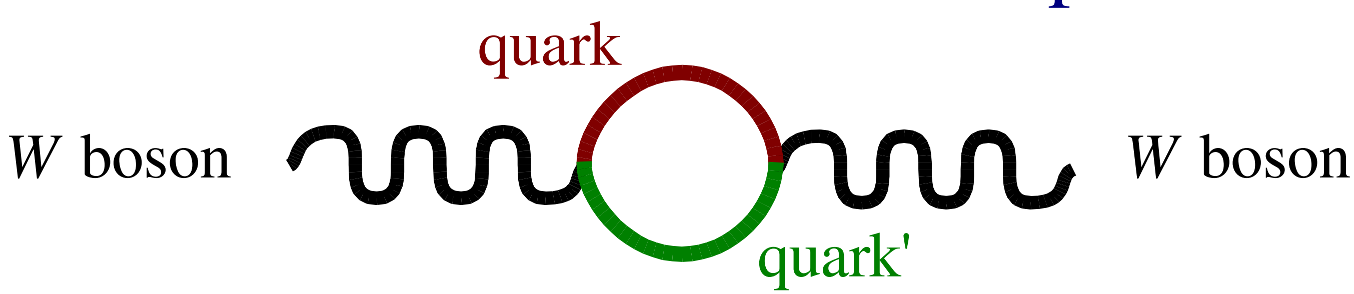
- Observed and studied in particle decays





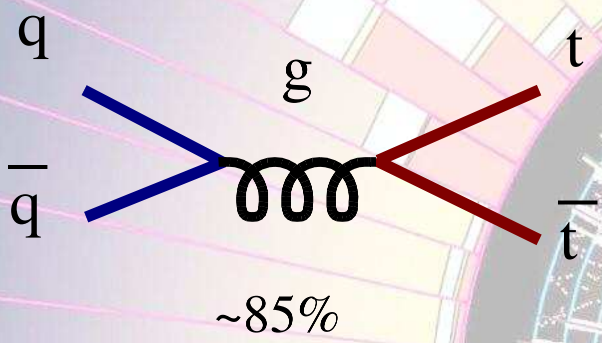
- Direct production of real *W* boson

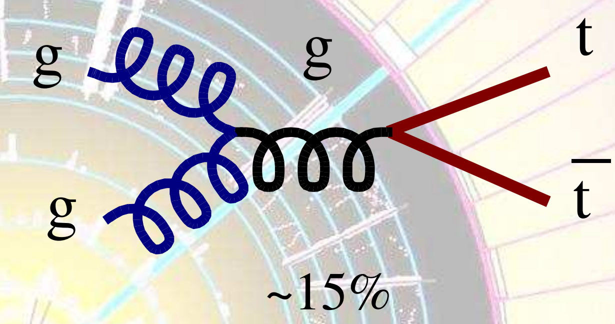
- Virtual corrections to electroweak processes



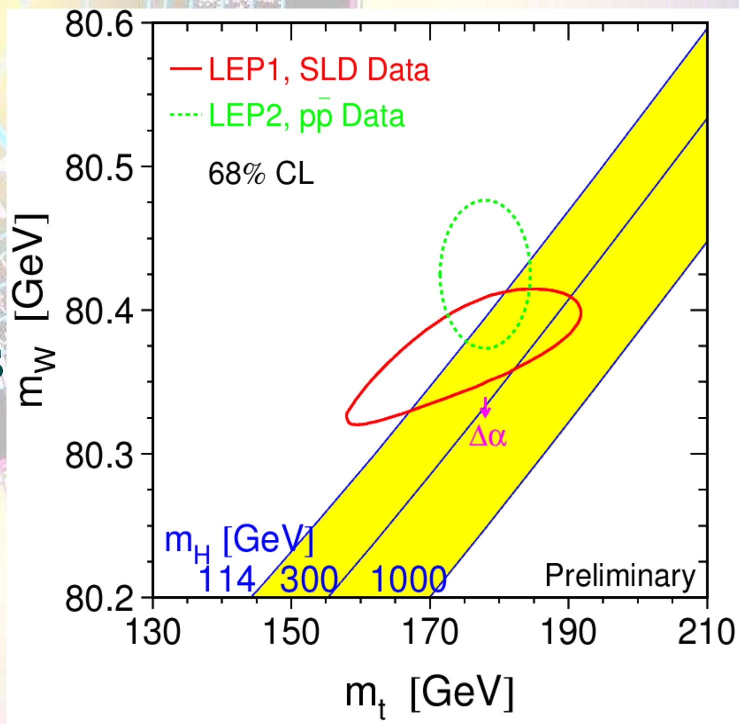
Tevatron Top Physics

- Top Pair Production at a Proton-Antiproton collider

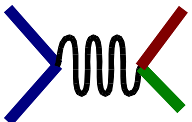
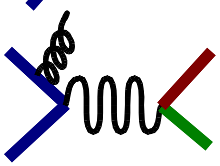
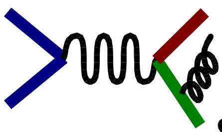
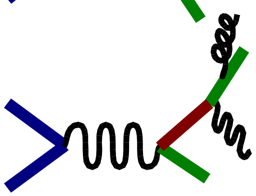




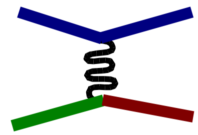
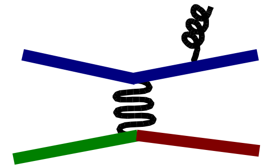
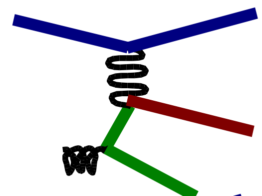
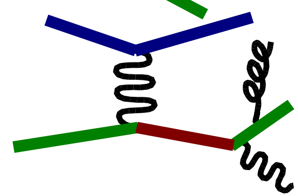
- Top Pair Studies at the Tevatron
  - Production cross section
  - Top mass
    - Implications for Standard Model Higgs
  - Look for new Physics
    - In top production and decay
  - Many more



Relative Contributions to NLO rate including Top Production and Decay

	s-channel	
	NLO rate	0.86pb
	Born level	65%
	Initial state	22%
	Final state	11.5%
	Decay	1.2%

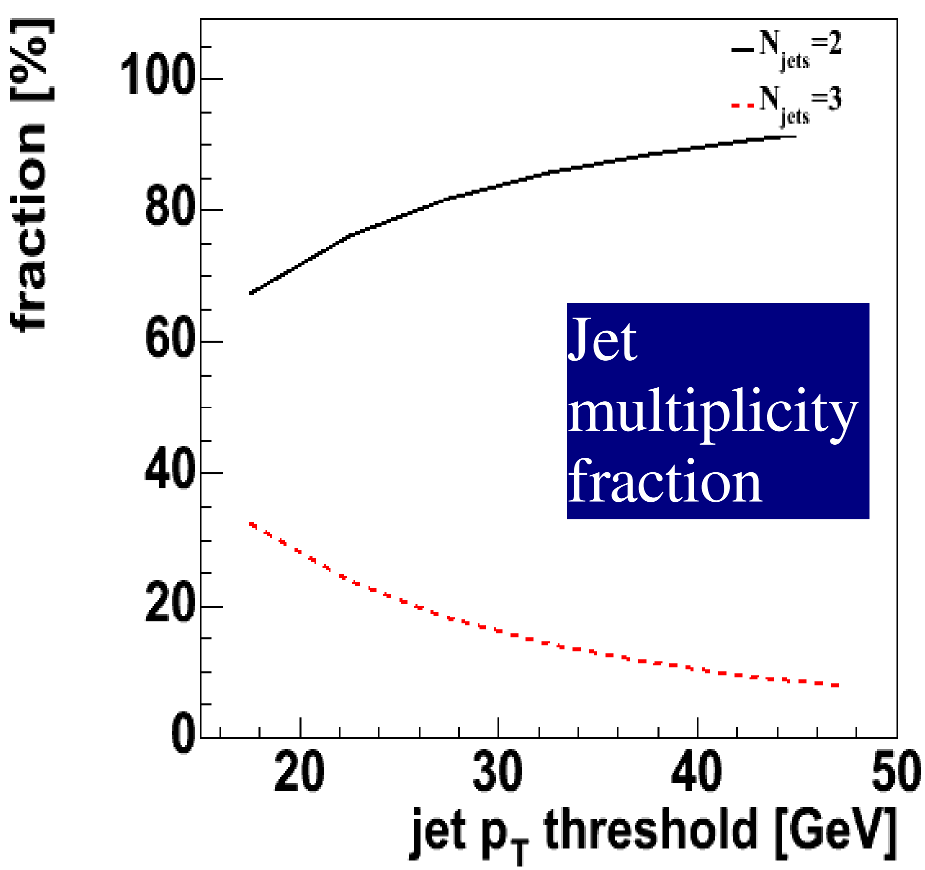
Cao, RS, Yuan hep-ph/0409040

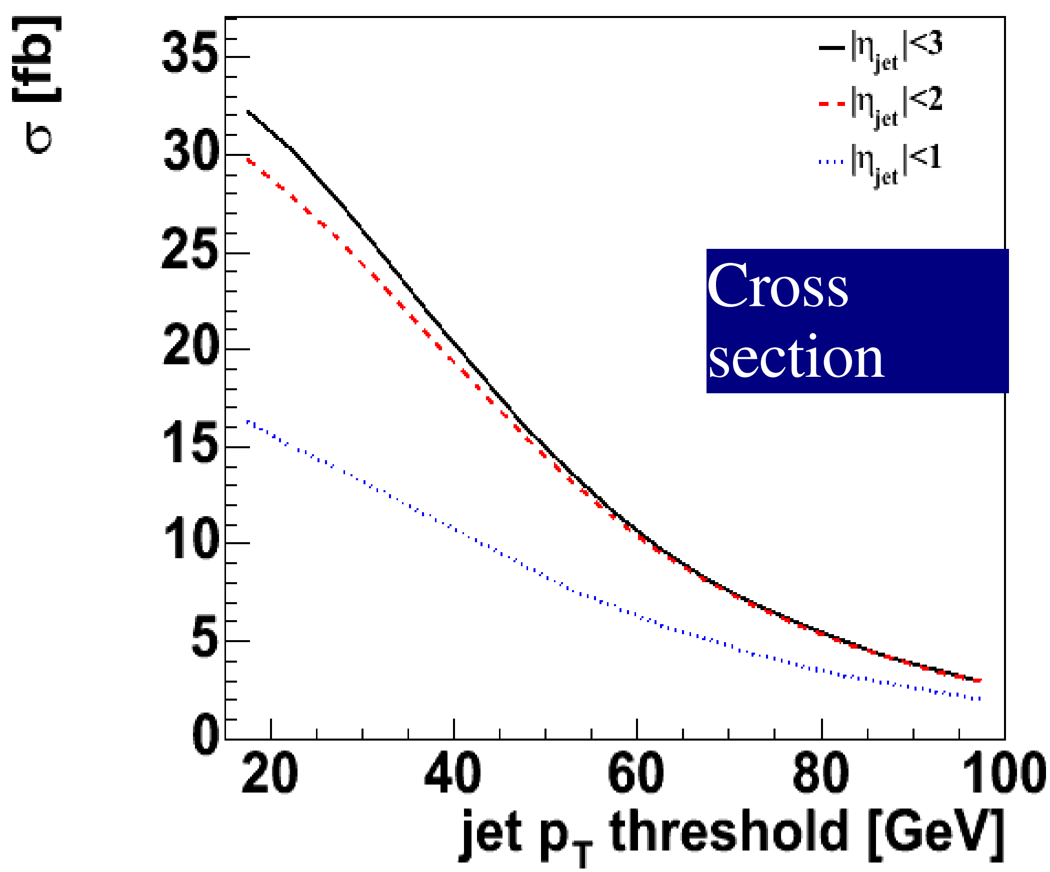
	t-channel	
	NLO rate	1.9pb
	Born level	105%
	Light quark	13%
	Heavy quark	-11%
	Decay	-7%

- O(as) corrections large for the s-channel
  - Only small rate correction for the t-channel
    - Decay correction is 2^{nd} order effect, top mass and top width

Kinematic effect of $O(\alpha_s)$ Corrections

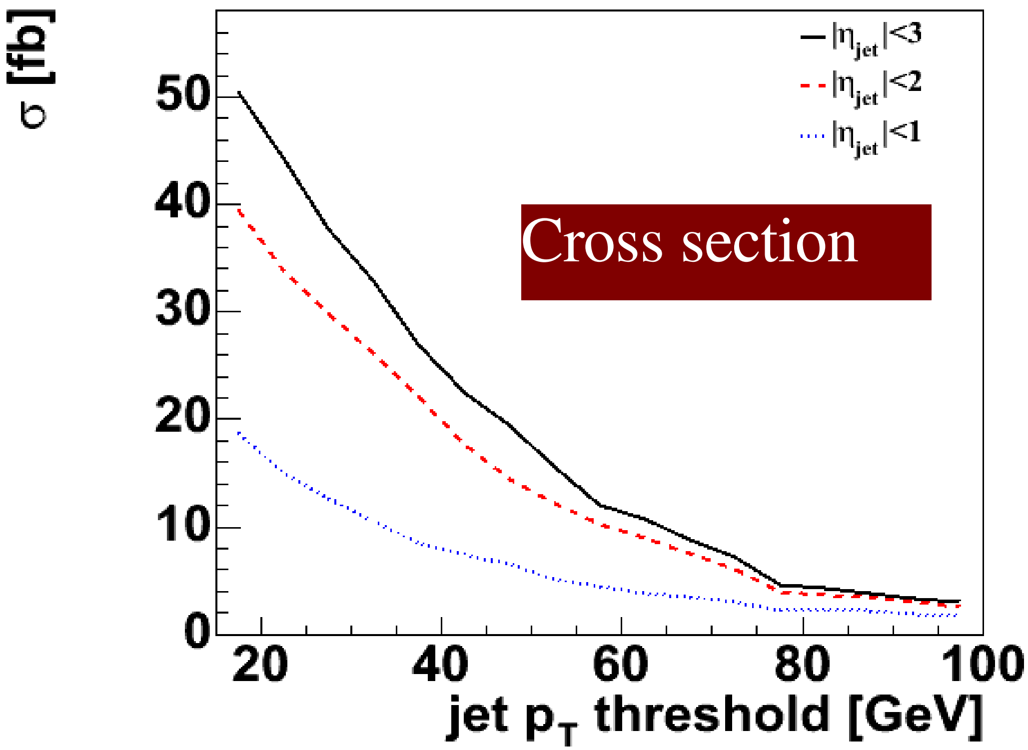
- After simple parton level selection cuts:
  - 1 lepton, p_T>15GeV, $|\eta|$<2, missing E_T>15GeV
  - ≥2 jets, p_T>15GeV, $|\eta|$<3
- Example: s-channel jet multiplicity

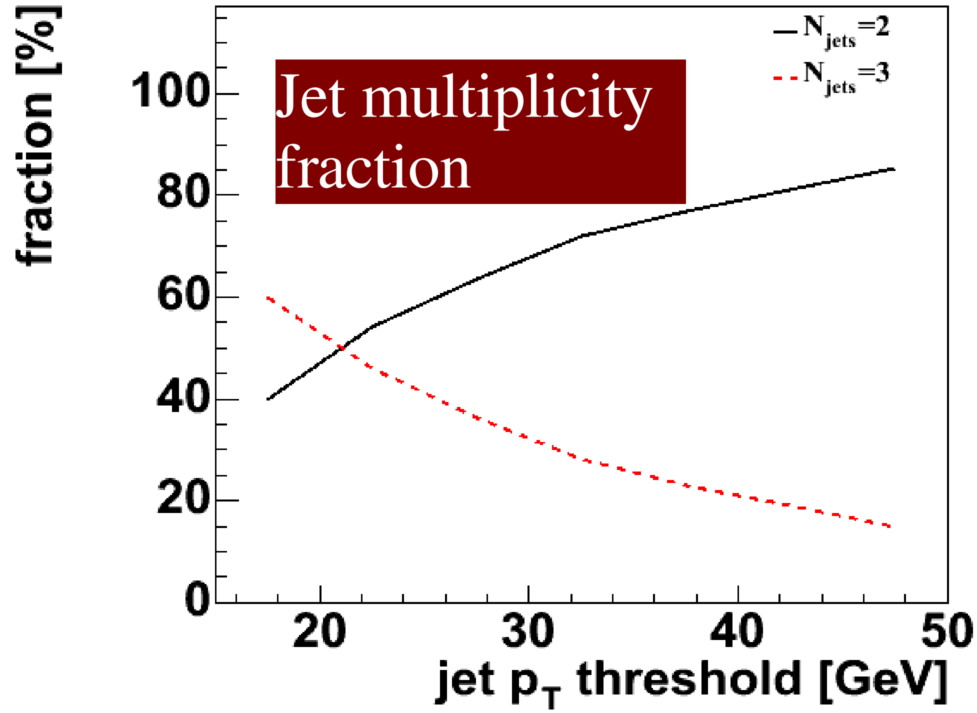


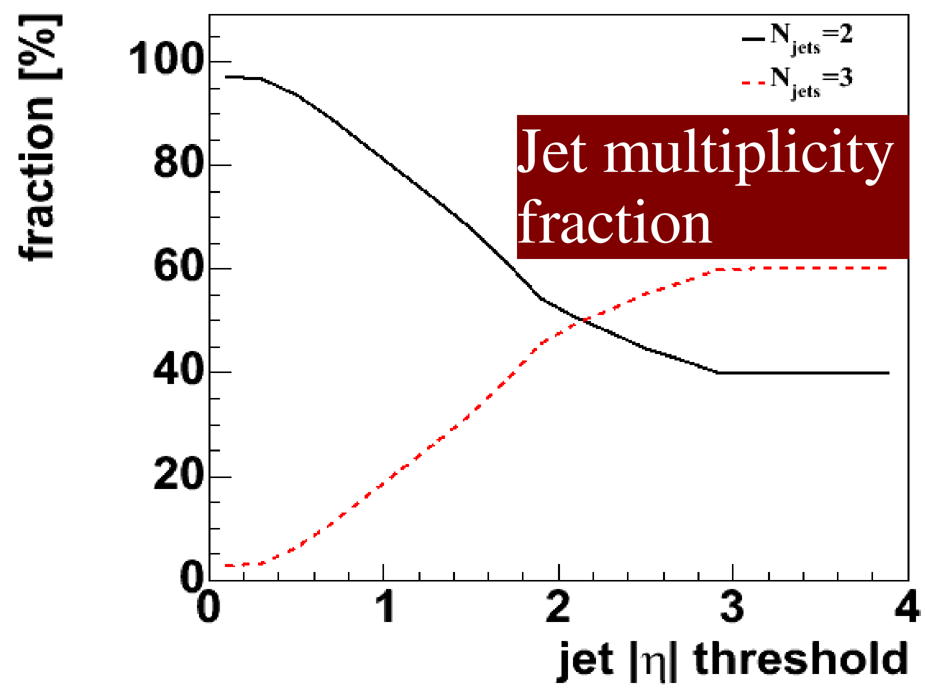


Cao, RS, Yuan hep-ph/0409040

Single Top t-channel at NLO



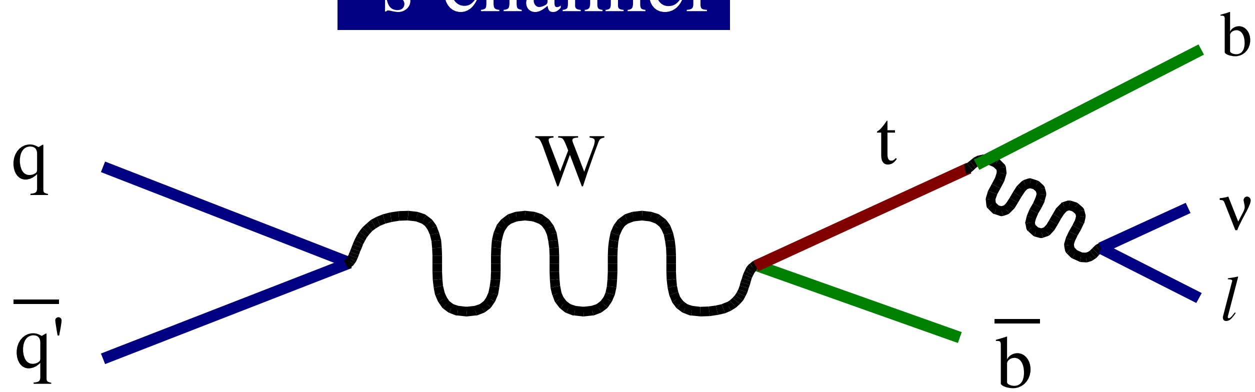




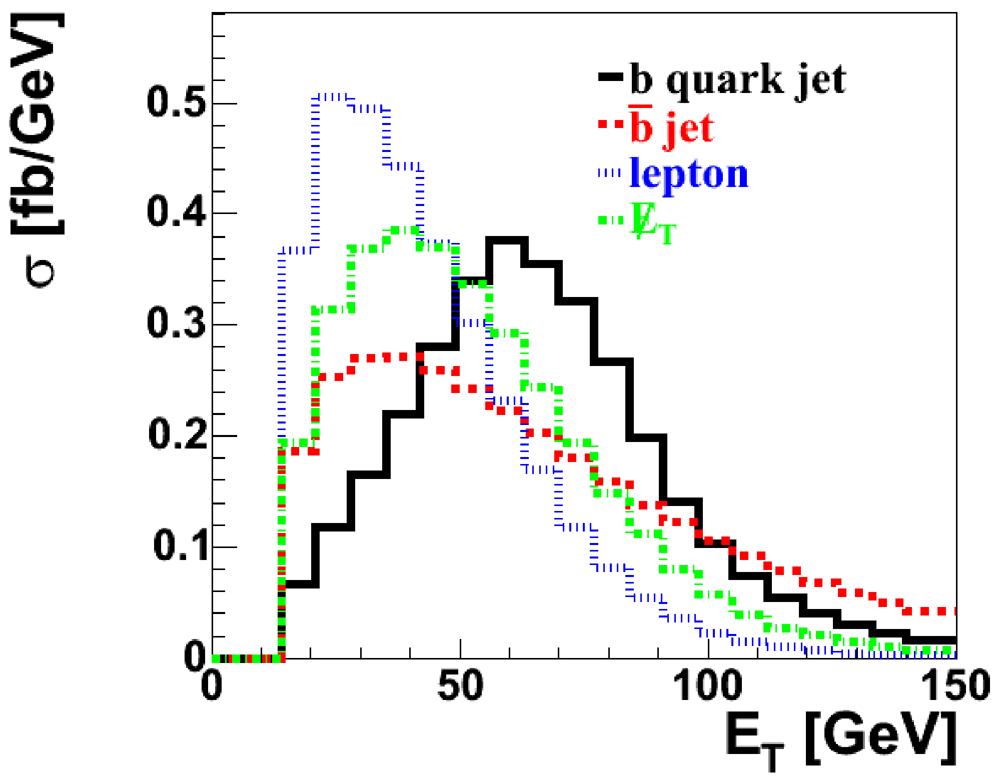
- After simple cuts
  - Large number of 3-jet events
    - Depends strongly on jet p_T and η cuts

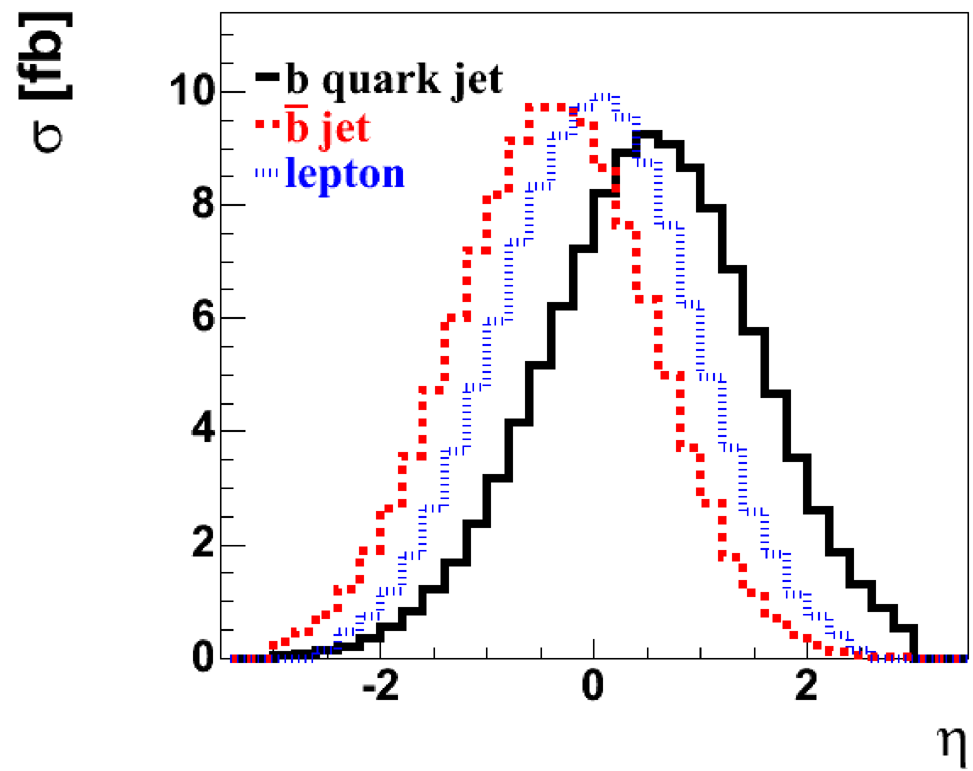
Tevatron Single Top Quark Production

s-channel

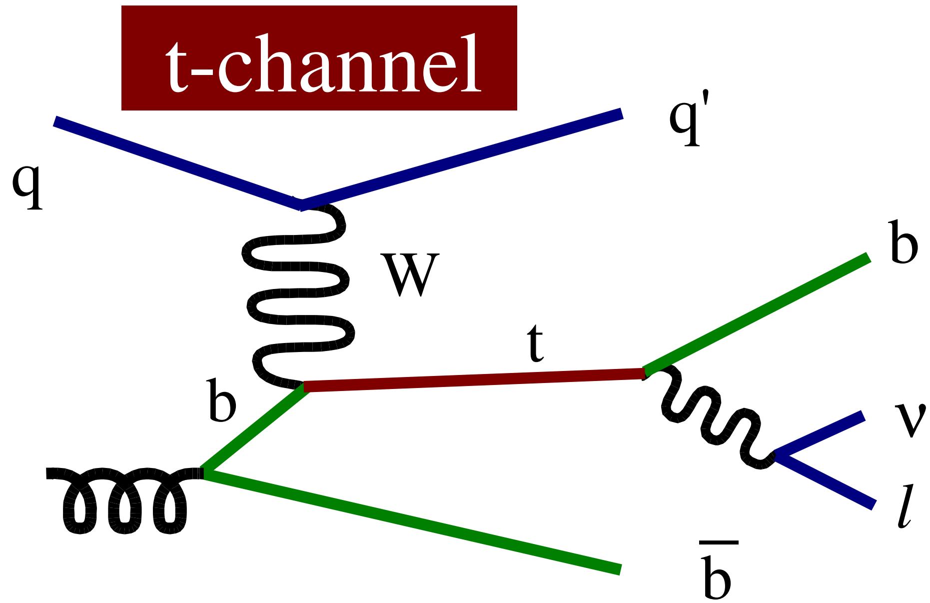


"tb"





Tevatron Single Top Quark Production



"tqb"